AN EFFICIENT ICI CANCELLATION TECHNIQUE FOR OFDM COMMUNICATION SYSTEMS

A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Electronics System and Communication

By

BRAHMAJI T.A.R.K.

Department of Electrical Engineering

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Under the Guidance of

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This is to certify that the thesis entitled **"AN EFFICIENT ICI CANCELLATION TECHNIQUE FOR OFDM COMMUNICATION SYSTEMS"** submitted by **BRAHMAJI T.A.R.K.** in partial fulfillment of the requirements for the award of **Master of Technology** in the Department of **Electrical Engineering**, with specialization in **'Electronics System and Communication'** at **National Institute of Technology, Rourkela** (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date :
Place :

PROF. SUSMITA DAS
SUPERVISOR

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BRAHMAJI T.A.R.K.
M. Tech (Electronics System and Communication)

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ABSTRACT

With the rapid growth of digital communication in recent years, the need for high speed data transmission is increased. Moreover, future wireless systems are expected to support a wide range of services which includes video, data and voice. OFDM is a promising candidate for achieving high data rates in mobile environment because of its multicarrier modulation technique and ability to convert a frequency selective fading channel into several nearly flat fading channels. Now OFDM is being widely used in wireless communications standards, such as IEEE 802.11a, the multimedia mobile access communication (MMAC), and the HIPERLAN/2. However, one of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes intercarrier interference (ICI).

A well known problem of orthogonal frequency division multiplexing (OFDM), however, is its sensitivity to frequency offset between the transmitted and received signals, which may be caused by Doppler shift in the channel, or by the difference between the transmitter and receiver local oscillator frequencies. This carrier frequency offset causes loss of orthogonality between sub-carriers and the signals transmitted on each carrier are not independent of each other. The orthogonality of the carriers is no longer maintained, which results in inter-carrier interference (ICI). The undesired ICI degrades the performance of the system. Depending on the Doppler spread in the channel and the block length chosen for transmission, ICI can potentially cause a severe deterioration of quality of service (QOS) in OFDM systems. ICI mitigation techniques are essential in improving the performance of an OFDM system in an environment which induces frequency offset error in the transmitted signal. The comparisons of these schemes in terms of various parameters will be useful in determining the choice of ICI mitigation techniques for different applications and mobile environments.

This project investigates an efficient ICI cancellation method termed ICI self-cancellation scheme for combating the impact of ICI on OFDM systems. The ICI self-cancellation scheme is a technique in which redundant data is transmitted onto adjacent sub-carriers such that the ICI between adjacent sub-carriers cancels out at the receiver. The main idea is one data symbol is modulated onto a group of adjacent subcarriers with a group of weighting coefficients. By doing so, the ICI signals generated within a group

can be “self-cancelled” each other. At the receiver side, by linearly combining the received signals on these subcarriers with proposed coefficients, the residual ICI contained in the received signals can then be further reduced. The carrier-to-interference power ratio (CIR) can be increased by 15 and 30 dB when the group size is two or three, respectively, for a channel with a constant frequency offset. Although the proposed scheme causes a reduction in bandwidth efficiency, it can be compensated, by using larger signal alphabet sizes in modulation. The average carrier-to-interference power ratio (CIR) is used as the ICI level indicator, and a theoretical CIR expression is derived for the proposed scheme. The proposed scheme provides significant CIR improvement, which has been studied theoretically and supported by simulations. Simulation results show that under the condition of the same bandwidth efficiency and larger frequency offsets, the proposed OFDM system using the ICI self-cancellation scheme [26] performs much better than standard OFDM systems in AWGN channel with large Doppler frequencies. In addition, since no channel equalization is needed for reducing ICI, the proposed scheme is therefore beneficial in implementation issue without increasing system complexity.

LIST OF ACRONYMS

ADC	Analog to Digital Converter
AWGN	Additive White Gaussian Noise
ADSL	Asymmetric Digital Subscriber Lines
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
CIR	Carrier to interference power ratio
DAB	Digital Audio Broadcast
FFT	Fast Fourier Transform
DAC	Digital to Analog Converter
DSL	Digital Subscriber Line
DSP	Digital Signal Processing
DVB	Digital Video Broadcast
FDMA	Frequency Division Multiple Access
GMSK	Gaussian Minimum Shift Keying
GPRS	General packet Radio Service
GSM	Global System for Mobile Communication
HDSL	High speed Digital Subscriber Line
HDTV	High Definition Television
IFFT	Inverse Fast Fourier Transform
ICI	Inter Carrier Interference
ISI	Inter Symbol Interference
ISP	Improved Sinc Power Pulse
MC	Multicarrier Communication
MCM	Multi Carrier Modulation
OFDM	Orthogonal Frequency Division Multiplexing
PSK	Phase Shift Keying
PAPR	Peak to Average Power Ratio

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RC	Raised Cosine Pulse
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
VHDSL	Very High speed Digital Subscriber Line
VLSI	Very Large Scale Integration
WLAN	Wireless Local Area Network

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Chapter **1**

introduction

INTRODUCTION

1.1 INTRODUCTION

The ever increasing demand for very high rate wireless data transmission calls for technologies which make use of the available electromagnetic resource in the most intelligent way. Key objectives are spectrum efficiency (bits per second per Hertz), robustness against multipath propagation, range, power consumption, and implementation complexity. These objectives are often conflicting, so techniques and implementations are sought which offer the best possible tradeoff between them. The Internet revolution has created the need for wireless technologies that can deliver data at high speeds in a spectrally efficient manner. However, supporting such high data rates with sufficient robustness to radio channel impairments requires careful selection of modulation techniques. Currently, the most suitable choice appears to be OFDM (Orthogonal Frequency Division Multiplexing).Orthogonal frequency division multiplexing (OFDM) is becoming the chosen modulation technique for wireless communications. OFDM can provide large data rates with sufficient robustness to radio channel impairments.

Orthogonal Frequency Division Multiplexing (OFDM) is a special form of multi carrier modulation technique which is used to generate waveforms that are mutually orthogonal. In an OFDM scheme, a large number of orthogonal, overlapping, narrow band sub-carriers are transmitted in parallel. These carriers divide the available transmission bandwidth. The separation of the sub-carriers is such that there is a very compact spectral utilization. With OFDM, it is possible to have overlapping sub channels in the frequency domain, thus increasing the transmission rate. In order to avoid a large number of modulators and filters at the transmitter and complementary filters and demodulators at the receiver, it is desirable to be able to use modern digital signal processing techniques, such as fast Fourier transform (FFT). After more than forty years of research and development carried out in different places, OFDM is now being widely implemented in high-speed digital communications. OFDM has been accepted as standard in several wire line and wireless applications. Due to the recent advancements in digital signal processing (DSP) and very large-scale integrated circuits (VLSI) technologies, the initial obstacles of OFDM implementations do not exist anymore. In a basic communication system, the data are modulated onto a single carrier frequency. The available bandwidth is then totally occupied by each symbol. This kind of system can lead to inter-symbol-interference (ISI) in case of frequency selective channel. The basic idea of OFDM is to divide the available spectrum into several orthogonal sub channels so that each narrowband sub channels experiences almost flat fading. Many research centers in the world have specialized teams working in the optimization of OFDM systems. The attraction of OFDM is mainly because of its way of handling the multipath interference at the receiver. Multipath phenomenon generates two effects (a) Frequency selective fading and (b) Intersymbol interference (ISI). The "flatness" perceived by a narrowband channel overcomes the frequency selective fading. On the other hand, modulating symbols at a very low rate makes the symbols much longer than channel impulse response and hence reduces the ISI. Use of suitable error correcting codes provides more robustness against frequency selective fading. The insertion of an extra guard interval between consecutive OFDM symbols can reduce the effects of ISI even more. The use of FFT technique to implement modulation and demodulation functions makes it computationally more efficient. OFDM systems have gained an increased interest during the last years. It is used in the European digital broadcast radio system, as well as in wired environment such as asymmetric digital subscriber lines (ADSL). This technique is used in digital subscriber lines (DSL) to provides high bit rate over a twisted-pair of wires.

The major advantages of OFDM are its ability to convert a frequency selective fading channel into several nearly flat fading channels and high spectral efficiency. However, one of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes attenuation and rotation of subcarriers, and intercarrier interference (ICI) [1,2]. The undesired ICI degrades the performance of the system.

1.2 HISTORY OF MOBILE WIRELESS COMMUNICATIONS

The history of mobile communication [3,4] can be categorized into 3 periods:

(a). The pioneer era

(b). The pre-cellular era

(c) The cellular era

In the pioneer era, a great deal of the fundamental research and development in the field of wireless communications took place. The postulates of electromagnetic (EM) waves by James Clark Maxwell during the 1860s in England, the demonstration of the existence of these waves by Heinrich Rudolf Hertz in 1880s in Germany and the invention and first demonstration of wireless telegraphy by Guglielmo Marconi during the 1890s in Italy were representative examples from Europe. Moreover, in Japan, the Radio Telegraph Research Division was established as a part of the Electro technical Laboratory at the Ministry of Communications and started to research wireless telegraph in 1896.

From the fundamental research and the resultant developments in wireless telegraphy, the application of wireless telegraphy to mobile communication systems started from the 1920s. This period, which is called the pre-cellular era, began with the first land-based mobile wireless telephone system installed in 1921 by the Detroit Police Department to dispatch patrol cars, followed in 1932 by the New York City Police Department. These systems were operated in the 2MHz frequency band.

In 1946, the first commercial mobile telephone system, operated in the 150MHz frequency band, was set up by Bell Telephone Laboratories in St. Louis. The demonstration system was a simple analog communication system with a manually operated telephone exchange. Subsequently, in 1969, a mobile duplex communication system was realized in the 450MHz frequency band. The telephone exchange of this modified system was operated automatically. The new system, called the Improved Mobile Telephone System (IMTS), was widely installed in the United States. However, because of its large coverage area, the system could not manage a large number of users or allocate the available frequency bands efficiently.

The cellular zone concept was developed to overcome this problem by using the propagation characteristics of radio waves. The cellular zone concept divided a large coverage area into many smaller zones. A frequency channel in one cellular zone is used in another cellular zone. However, the distance between the cellular zones that use the same frequency channels is sufficiently long to ensure that the probability of interference is quite low. The use of the new cellular zone concept launched the third era, known as the cellular era.

So far, the evolution of the analog cellular mobile communication system is described. There were many problems and issues, for example, the incompatibility of the various systems in each country or region, which precluded roaming. In addition, analog mobile communication systems were unable to ensure sufficient capacity for the increasing number of users, and the speech quality was not good. To solve these problems, the R&D of cellular mobile communication systems based on digital radio transmission schemes was initiated. These new mobile communication systems became known as the second generation (2G) of mobile communication systems, and the analog cellular era is regarded as the first generation (1G) of mobile communication systems [5,6].

1G analog cellular systems were actually a hybrid of analog voice channels and digital control channels. The analog voice channels typically used Frequency Modulation (FM) and the digital control channels used simple Frequency Shift keying (FSK) modulation. The first commercial analog cellular systems include Nippon Telephone and Telegraph (NTT) Cellular – Japan, Advanced Mobile Phone Service (AMPS) – US, Australia, China, Southeast Asia, Total Access Communications system (TACS) - UK, and Nordic Mobile Telephone (NMT) – Norway, Europe.

2G digital systems use digital radio channels for both voice (digital voice) and digital control channels. 2G digital systems typically use more efficient modulation technologies, including Global System for Mobile communications (GSM), which uses a standard 2-level Gaussian Minimum Shift Keying (GMSK). Digital radio channels offer a universal data transmission system, which can be divided into many logical channels that can perform different services. 2G also uses multiple access (or multiplexing) technologies to allow more customers to share individual radio channels or use narrow channels to allow more radio channels into a limited amount of radio spectrum band. The 3 basic types of access technologies used in 2G are: frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). The technologies either reduce the RF channel bandwidth (FDMA), share a radio channel by assigning users to brief timeslot (TDMA), or divide a wide RF channel into many different coded channels (CDMA). Improvements in modulation techniques and multiple access technologies amongst other technologies inadvertently led to 2.5G and 3G. For example, EDGE can achieve max 474 kbps by using 8-PSK with the existing GMSK. This is 3x more data transfer than GPRS.

1.3 GENERATIONS OF TELECOMMUNICATION

First Generation (1G) is described as the early analogue cellular phone technologies. 1G analog cellular systems were actually a hybrid of analog voice channels and digital control channels. The analog voice channels typically used Frequency Modulation (FM) and the digital control channels used simple Frequency Shift keying (FSK) modulation. The first commercial analog cellular systems include Nippon Telephone and Telegraph (NTT) Cellular – Japan, Advanced Mobile Phone Service (AMPS) – US, Australia, China, Southeast Asia, Total Access Communications system (TACS) - UK, and Nordic Mobile Telephone (NMT) – Norway, Europe. NMT and AMPS cellular technologies fall under this categories.

Second Generation (2G) described as the generation first digital fidely used cellular phones systems. 2G digital systems use digital radio channels for both voice (digital voice) and digital control channels. GSM technology is the most widely used 2G technologies. 2G digital systems typically use more efficient modulation technologies, including Global System for Mobile communications (GSM), which uses a standard 2-level Gaussian Minimum Shift Keying (GMSK). This gives digital speech and some limited data capabilities (circuit switched 9.6kbits/s). Other 2G technologies are IS-95 CDMA, IS-136 TDMA and PDC. 2G also uses multiple access (or multiplexing) technologies to allow more customers to share individual radio channels or use narrow channels to allow more radio channels into a limited amount of radio spectrum band. The 3 basic types of access technologies used in 2G are: frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). The technologies either reduce the RF channel bandwidth (FDMA), share a radio channel by assigning users to brief timeslot (TDMA), or divide a wide RF channel into many different coded channels (CDMA).

Two and Half Generation (2.5G) is an enhanced version of 2G technology. 2.5G gives higher data rate and packet data services. GSM systems enhancements like GPRS and EDGE are considered to be in 2.5G technology. The so-called 2.5G technology represent an intermediate upgrade in data rates available to mobile users.

Third Generation (3G) mobile communication systems often called with names 3G, UMTS and WCDMA promise to boost the mobile communications to the new speed limits. The promises of third generation mobile phones are fast Internet surfing advanced value-added services and video telephony. Third-generation wireless systems will handle services up to 384 kbps in wide area applications and up to 2 Mbps for indoor applications.

Fourth Generation (4G) is intended to provide high speed, high capacity, low cost per bit, IP based services. The goal is to have data rates up to 20 Mbps. Most probable the 4G network would be a network which is a combination of different technologies, for example, current cellular networks, 3G cellular network and wireless LAN, working together using suitable interoperability protocols.

A HISTORY OF OFDM TECHNIQUE

1957	Kineplex, multi-carrier high frequency (HF) modem
1966	R. W. Chang, Bell Labs, OFDM paper patent
1971	Weinstein & Ebert proposed the use of FFT and guard interval
1985	Cimini described the use of OFDM for mobile communications
1995	ETSI established the first OFDM based standard, digital audio broadcasting (DAB) standard
1997	Broadband internet with asymmetrical digital subscriber line (ADSL) was employed
1998	Magic WAND project demonstrated OFDM modems for wireless LAN
1999	IEEE 802.11a and HIPERLAN/2 standards were established for WLAN
2000	Vector OFDM (V-OFDM) for a fixed wireless access
2001	OFDM was considered for the IEEE 802.11g and the IEEE 802.16 standards

1.4 MOTIVATION:

OFDM is robust in adverse channel conditions and allows a high level of spectral efficiency. Multiple access techniques which are quite developed for the single carrier modulations (e.g. TDMA, FDMA) had made possible of sharing one communication medium by multiple number of users simultaneously. The sharing is required to achieve high capacity by simultaneously allocating the available bandwidth to multiple users without severe degradation in the performance of the system. FDMA and TDMA are the well known multiplexing techniques used in wireless communication systems.

While working with the wireless systems using these techniques, various problems encountered are (1) multi-path fading (2) time dispersion which lead ISI (3) lower bit rate capacity (4) requirement of larger transmit power for high bit rate and (5) less spectral efficiency. Disadvantage of FDMA technique is its Bad Spectrum Usage. Disadvantages of TDMA technique is Multipath Delay spread problem. In a typical terrestrial broadcasting, the transmitted signal arrives at the receiver using various paths of different lengths. Since multiple versions of the signal interfere with each other, it becomes difficult to extract the original information.

Orthogonal Frequency Division Multiplexing (OFDM) has recently gained fair degree of prominence among modulation schemes due to its intrinsic robustness to frequency selective Multipath fading channels. OFDM system also provides higher spectrum efficiency and supports high data rate transmission. This is one of the main reasons to select OFDM a candidate for systems such as Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), Digital Subscriber Lines (DSL), and Wireless local area networks (HiperLAN/2), and in IEEE 802.11a, IEEE 802.11g.

The focus of future fourth-generation (4G) mobile systems is on supporting high data rate services such as deployment of multi-media applications which involve voice, data, pictures, and video over the wireless networks. At this moment, the data rate envisioned for 4G networks is 1 GB/s for indoor and 100Mb/s for outdoor environments. Orthogonal frequency division multiplexing (OFDM) is a promising candidate for 4G systems because of its robustness to the multipath environment.

One of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes intercarrier interference (ICI). The undesired ICI degrades the performance of the system. Thus, an accurate and efficient Intercarrier Interference (ICI) reduction procedure is necessary to demodulate the received data. So, I have focused on ICI self cancellation technique which eliminates the inter carrier interference in sub-carriers of OFDM symbols in a OFDM signal.

1.5 LITERATURE SURVEY

In 1971, Weinstein and Ebert proposed a modified OFDM system [7] in which the discrete Fourier Transform (DFT) was applied to generate the orthogonal subcarriers waveforms in stead of the banks of sinusoidal generators. Their scheme reduced the implementation complexity significantly, by making use of the inverse DFT (IDFT) modules and the digital-to-analog converters. In their proposed model, baseband signals were modulated by the IDFT in the transmitter and then demodulated by DFT in the receiver. Therefore, all the subcarriers were overlapped with others in the frequency domain, while the DFT modulation still assures their orthogonality.

Cyclic prefix (CP) or cyclic extension was first introduced by Peled and Ruiz in 1980 [8] for OFDM systems. In their scheme, conventional null guard interval is substituted by cyclic extension for fully-loaded OFDM modulation. As a result, the orthogonality among the subcarriers was guaranteed. With the trade-off of the transmitting energy efficiency, this new scheme can result in a phenomenal ISI (Inter Symbol Interference) reduction. Hence it has been adopted by the current IEEE standards. In 1980, Hirosaki introduced an equalization algorithm to suppress both inter symbol interference (ISI) and ICI [9], which may have resulted from a channel distortion, synchronization error, or phase error. In the meantime, Hirosaki also applied QAM modulation, pilot tone, and trellis coding techniques in his high-speed OFDM system, which operated in voice-band spectrum.

In 1985, Cimini introduced a pilot-based method to reduce the interference emanating from the multipath and co-channels [10]. In the 1990s, OFDM systems have been exploited for high data rate communications. In the IEEE 802.11 standard, the carrier frequency can go up as high as 2.4 GHz or 5 GHz. Researchers tend to pursue OFDM operating at even much higher frequencies nowadays. For example, the IEEE 802.16 standard proposes yet higher carrier frequencies ranging from 10 GHz to 60 GHz. However, one of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes intercarrier interference (ICI). The undesired ICI degrades the performance of the system. ICI self-cancellation [15] is a scheme that was introduced by Yuping Zhao and Sven-Gustav Häggman in 2001 to combat and suppress ICI in OFDM.

1.6 CONTRIBUTION:

Using MATLAB, simulation of OFDM was done with different modulation techniques using self cancellation technique. The digital modulation schemes such as BPSK and QPSK were selected to assess the performance of the designed OFDM system by finding their bit error rate (BER) for different values of signal to noise ratio (SNR). In this project, I have focused on the problem of ICI reduction using self cancellation scheme [26] and compared with standard OFDM system. Different modulation techniques are considered for ICI reduction and compared with each other for their performances. I have also briefly discussed OFDM and its advantages and disadvantages as compared to single carrier modulation technique.

1.7 OBJECTIVE AND OUTLINE OF THESIS

The main objective of this thesis is to minimize ICI in OFDM by different methods of ICI reduction. Several methods have been presented to reduce ICI, including frequency domain equalization [11,12], windowing at the receiver [13,14], ICI self-cancellation scheme [15,16,26], and the use of pulse shaping [17,18,19].

This report is organized as follows: In Chapter 2, the basics of OFDM are presented. In Chapter 3, the digital modulation scheme used for simulation of OFDM system is presented and also the effect of channel is discussed. In Chapter 4, Different methods of ICI reduction are presented. In Chapter 5, ICI reduction using self cancellation is considered in detail. BPSK and QPSK modulation techniques are considered and compared with each other for their performances. Chapter 6 presents theoretical and Simulation Results. Chapter 7 concludes the report and future works are also outlined.

Chapter 2

Basics of OFDM

BASICS OF OFDM

2.1 INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) has grown to be the most popular communications systems in high speed communications. OFDM technology is the future of wireless communications.

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier transmission technique, which divides the bandwidth into many carriers, each one is modulated by a low rate data stream [20,21]. In term of multiple access technique, OFDM is similar to FDMA in that the multiple user access is achieved by subdividing the available bandwidth into multiple channels that are then allocated to users. However, OFDM uses the spectrum much more efficiently by spacing the channels much closer together. This is achieved by making all the carriers orthogonal to one another, preventing interference between the closely spaced carriers.

2.2 EVOLUTION OF OFDM

The evolution of OFDM can be divided into three parts [22]. There are consists of Frequency Division Multiplexing (FDM), Multicarrier Communication (MC) and Orthogonal Frequency Division Multiplexing.

2.2.1 Frequency Division Multiplexing (FDM)

Frequency Division Multiplexing (FDM) has been used for a long time to carry more than one signal over a telephone line. FDM is the concept of using different frequency channels to carry the information of different users. Each channel is identified by the center frequency of transmission. To ensure that the signal of one channel did not overlap with the signal from an adjacent one, some gap or guard band was left between different channels. Obviously, this guard band will lead to inefficiencies which were exaggerated in the early days since the lack of digital filtering is made it difficult to filter closely packed adjacent channels.

2.2.2 Multicarrier Communication (MC)

The concept of multicarrier (MC) communications uses a form of FDM technologies but only between a single data source and a single data receiver [23]. As multicarrier communications was introduced, it enabled an increase in the overall capacity of communications, thereby increasing the overall throughput. Referring to MC as FDM, however, is somewhat misleading since the concept of multiplexing refers to the ability to add signals together. MC is actually the concept of splitting a signal into a number of signals, modulating each of these new signals over its own frequency channel, multiplexing these different frequency channels together in an FDM manner; feeding the received signal via a receiving antenna into a demultiplexer that feeds the different frequency channels to different receivers and combining the data output of the receivers to form the received signal.

2.2.3 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) is simply defined as a form of multi-carrier modulation where the carrier spacing is carefully selected so that each sub-carrier is orthogonal to the other sub-carriers. Orthogonality can be achieved by carefully selecting the sub-carrier frequencies. One of the ways is to select sub-carrier frequencies such that they are harmonics to each other.

2.3 ORTHOGONALITY

OFDM is simply defined as a form of multi-carrier modulation where the carrier spacing is carefully selected so that each sub carrier is orthogonal to the other sub carriers. Two signals are orthogonal if their dot product is zero. That is, if you take two signals multiply them together and if their integral over an interval is zero, then two signals are orthogonal in that interval. Orthogonality can be achieved by carefully selecting carrier spacing, such as letting the carrier spacing be equal to the reciprocal of the useful symbol period. As the sub carriers are orthogonal, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system. This results in no interference between the carriers, allowing them to be spaced as close as theoretically possible. Mathematically, suppose we have a set of signals ψ then

$$\int_a^{a+T} \Psi_p(t)\, \Psi_q^*(t) = \begin{cases} K & \text{for } p = q \\ 0 & \text{for } p \neq q \end{cases} \qquad \text{.........................2.1}$$

The signals are orthogonal if the integral value is zero over the interval [a a+T], where T is the symbol period. Since the carriers are orthogonal to each other the nulls of one carrier coincides with the peak of another sub carrier. As a result it is possible to extract the sub carrier of interest.

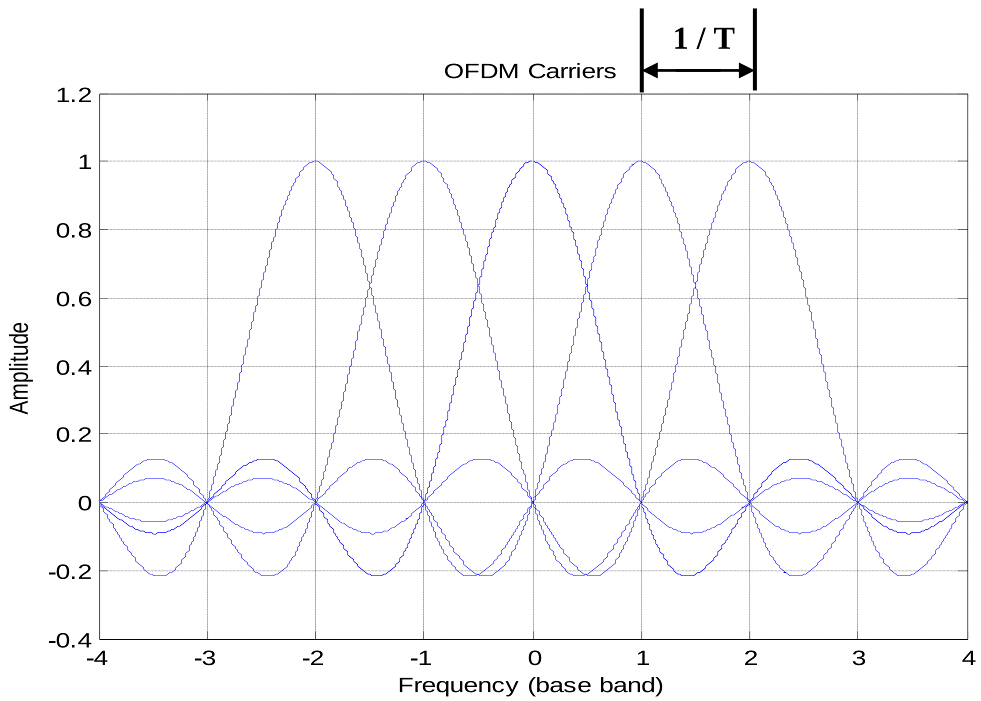


Fig. 2.1 Frequency spectrum of OFDM transmission.

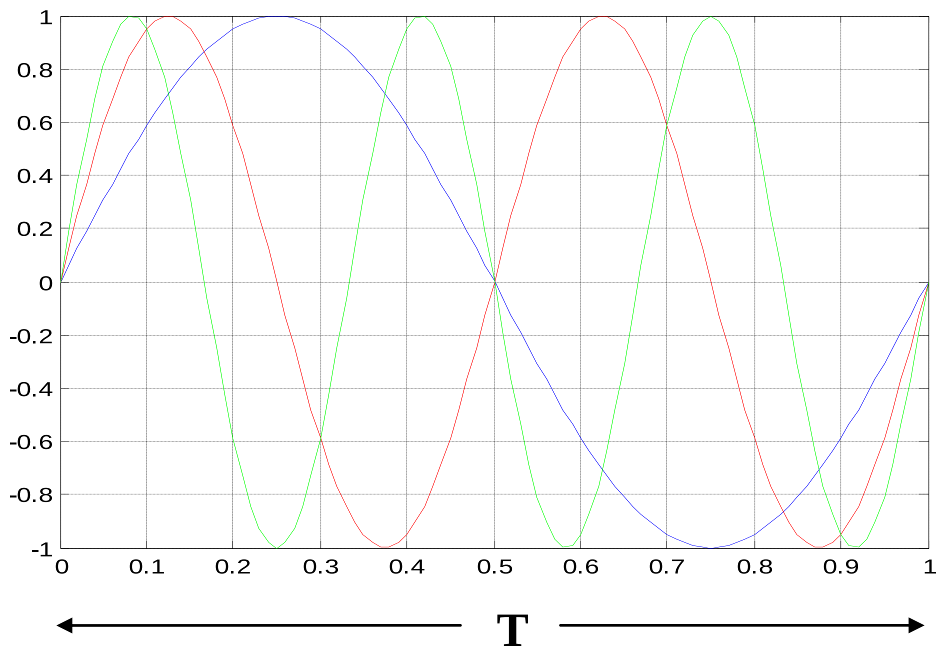


Fig. 2.2 Carrier signals in an OFDM transmission

OFDM transmits a large number of narrowband sub channels. The frequency range between carriers is carefully chosen in order to make them orthogonal each another. In fact, the carriers are separated by an interval of 1/T, where T represents the duration of an OFDM symbol. The frequency spectrum of an OFDM transmission is illustrated in figure 2.1. The figure indicates the spectrum of carriers significantly over laps over the other carrier. This is contrary to the traditional FDM technique in which a guard band is provided between each carrier. Each sinc of the frequency spectrum in the Fig 2.1 corresponds to a sinusoidal carrier modulated by a rectangular waveform representing the information symbol. One could easily notice that the frequency spectrum of one carrier exhibits zero-crossing at central frequencies corresponding to all other carriers. At these frequencies, the intercarrier interference is eliminated, although the individual spectra of subcarriers overlap. It is well known that orthogonal signals can be separated at the receiver by correlation techniques. The receiver acts as a bank of demodulators, translating each carrier down to baseband, the resulting signal then being integrated over a symbol period to recover the data. If the other carriers beat down to frequencies which, in the time domain means an integer number of cycles per symbol period (T), then the integration process results in a zero contribution from all these carriers. The waveforms of some of the carriers in an OFDM transmission are illustrated in Fig 2.2.

2.4 PRINCIPLE OF OFDM TRANSMISSION TECHNOLOGY

As stated above OFDM is a multi-carrier modulation technology where every sub-carrier is orthogonal to each other. The "orthogonal" part of the OFDM name indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. It is possible to arrange the carriers in an OFDM Signal so that the sidebands of the individual carriers overlap and the signals can still be received without adjacent carriers interference. In order to do this the carriers must be mathematically orthogonal. Two signals are orthogonal if their dot product is zero. That is, if we take two signals multiply them together and if their integral over an interval is zero, then two signals are orthogonal in that interval. Since the carriers are all sine/cosine wave, we know that area under one period of a sine or a cosine wave is zero which is as shown below.

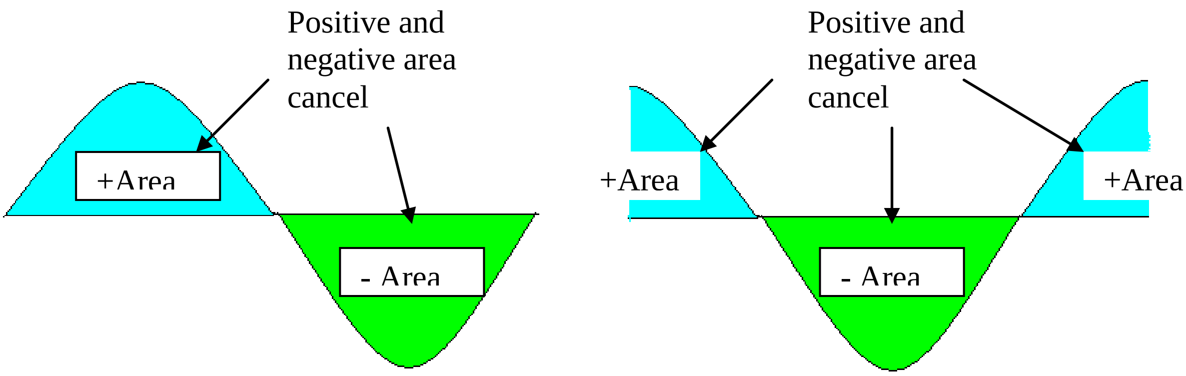


Fig. 2.3 The area under a sine and a cosine wave over one period is always zero.

If a sine wave of frequency m is multiplied by a sinusoid (sine or cosine) of a frequency n, then the product is given by

$$f(t) = \sin mwt \times \sin nwt \qquad \text{.........................2.2}$$

where both m and n are integers. By simple trigonometric relationship, this is equal to a sum of two sinusoids of frequencies (n-m) and (n+m). Since these two components are each a sinusoid, the integral is equal to zero over one period. The integral or area under this product is given by

$$= \int_0^{2\pi} \tfrac{1}{2}\cos(m-n)wt - \int_0^{2\pi} \tfrac{1}{2}\cos(m+n)wt \qquad \text{.........................2.3}$$

$$= 0 - 0$$

So when a sinusoid of frequency *n* multiplied by a sinusoid of frequency *m*, the area under the product is zero. In general for all integers *n* and *m*, sin *mx*, cos *mx*, cos *nx*, sin *nx* are all orthogonal to each other. These frequencies are called harmonics.

As the sub carriers are orthogonal, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system. This results in no interference between the carriers, allowing them to be spaced as close as theoretically possible. The orthogonality allows simultaneous transmission on a lot of sub-carriers in a tight frequency space without interference from each other.

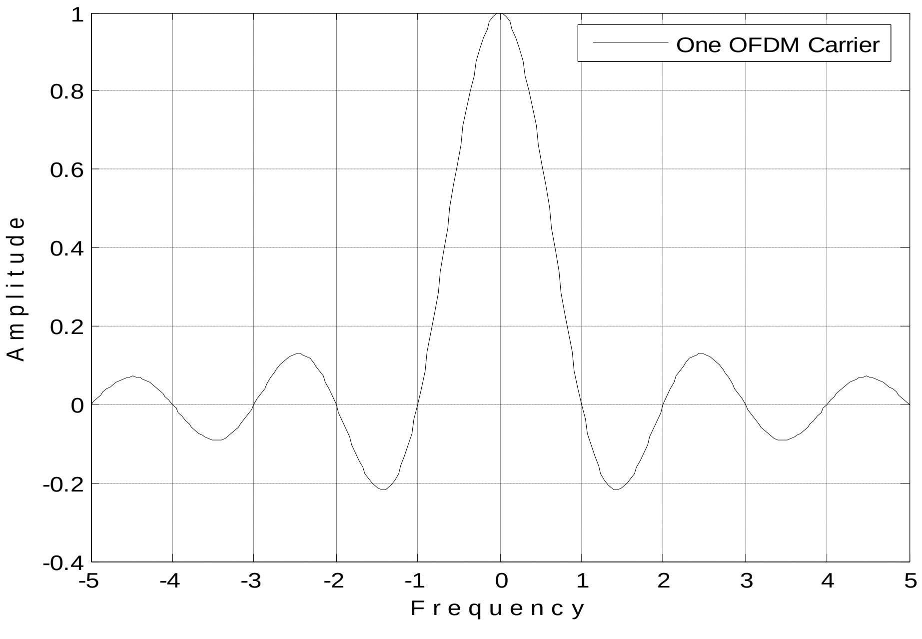


Fig. 2.4 Single Carrier of OFDM Signal

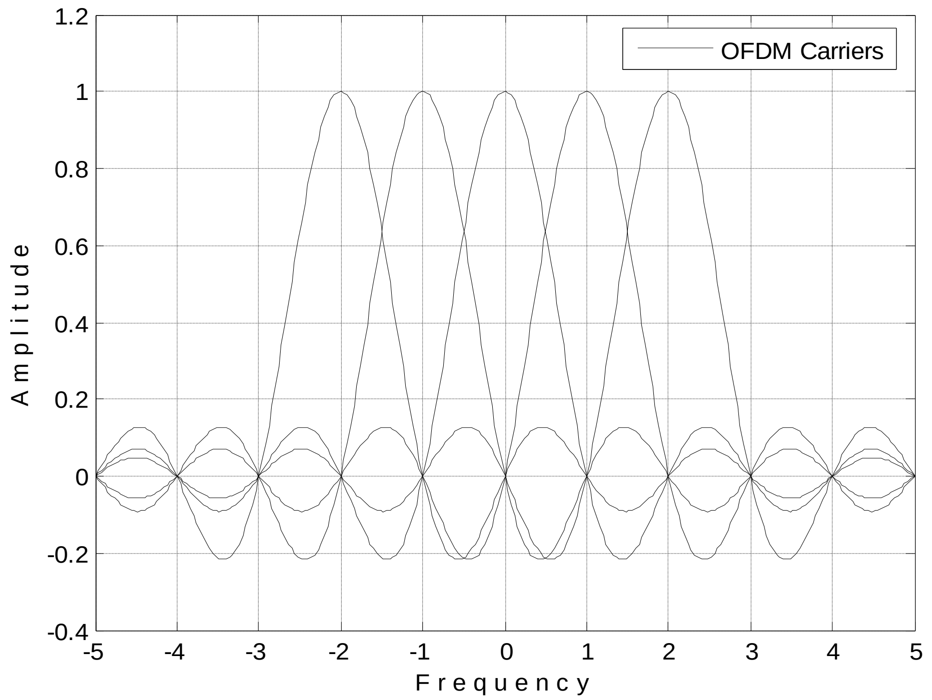


Fig. 2.5 5 carriers of OFDM Signal

So in the receiver side easily we can extract the individual sub-carriers. But in traditional FDM systems overlapping of carriers are not possible, rather a guard band is provided between each carrier to avoid inter-carrier interference which is as shown below.

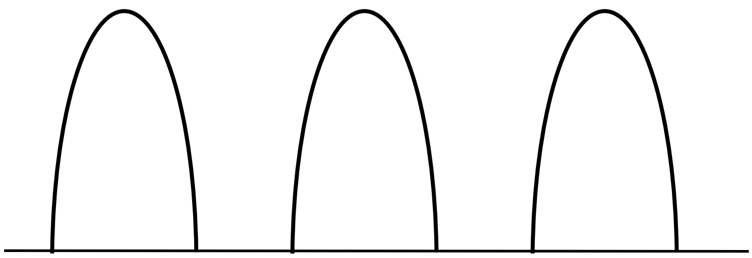


Fig. 2.6 - Spectrum of FDM

2.5 OFDM GENERATION AND RECEPTION

Figure 2.7 shows the block diagram of a typical OFDM transceiver. The transmitter section converts digital data to be transmitted, into a mapping of subcarrier amplitude and phase. It then transforms this spectral representation of the data into the time domain using an Inverse Discrete Fourier Transform (IDFT). The Inverse Fast Fourier Transform (IFFT) performs the same operations as an IDFT, except that it is much more computationally efficiency, and so is used in all practical systems. In order to transmit the OFDM signal the calculated time domain signal is then mixed up to the required frequency. The receiver performs the reverse operation of the transmitter, mixing the RF signal to base band for processing, then using a Fast Fourier Transform (FFT) to analyze the signal in the frequency domain. The amplitude and phase of the subcarriers is then picked out and converted back to digital data. The IFFT and the FFT are complementary function and the most appropriate term depends on whether the signal is being received or generated. In cases where the signal is independent of this distinction then the term FFT and IFFT is used interchangeably.

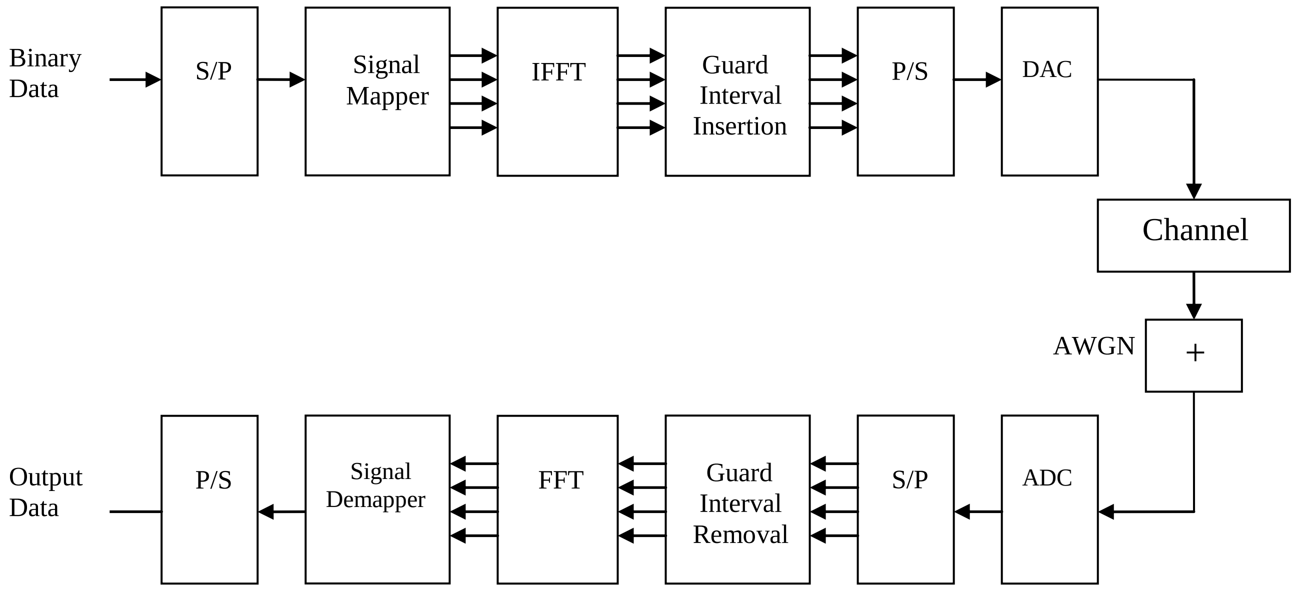


Fig. 2.7 – The basic block diagram of an OFDM system

The high data rate serial input bit stream is fed into serial to parallel converter to get low data rate output parallel bit stream. Input bit stream is taken as binary data. The low data rate parallel bit stream is modulated in Signal Mapper. Modulation can be BPSK, QPSK,QAM etc. The modulated data are served as input to inverse fast Fourier transform so that each subcarrier is assigned with a specific frequency. The frequencies selected are orthogonal frequencies. In this block, orthogonality in subcarriers is introduced. In IFFT, the frequency domain OFDM symbols are converted into time domain OFDM symbols. Guard interval is introduced in each OFDM symbol to eliminate inter symbol interference (ISI). All the OFDM symbols are taken as input to parallel to serial data. These OFDM symbols constitute a frame. A number of frames can be regarded as one OFDM signal. This OFDM signal is allowed to pass through digital to analog converter (DAC). In DAC the OFDM signal is fed to RF power amplifier for transmission. Then the signal is allowed to pass through additive white Gaussian noise channel (AWGN channel). At the receiver part, the received OFDM signal is fed to analog to digital converter (ADC) and is taken as input to serial to parallel converter. In these parallel OFDM symbols, Guard interval is removed and it is allowed to pass through Fast Fourier transform. Here the time domain OFDM symbols are converted into frequency domain. After this it is fed into Signal Demapper for demodulation purpose. And finally the low data rate parallel bit stream is converted into high data rate serial bit stream which is in form of binary.

2.5.1 Signal Mapping

A large number of modulation schemes are available allowing the number of bits transmitted per carrier per symbol to be varied. Digital data is transferred in an OFDM link by using a modulation scheme on each subcarrier. A modulation scheme is a mapping of data words to a real (In phase) and imaginary (Quadrature) constellation, also known as an IQ constellation. For example 256-QAM (Quadrature Amplitude Modulation) has 256 IQ points in the constellation constructed in a square with 16 evenly spaced columns in the real axis and 16 rows in the imaginary axis.

The number of bits that can be transferred using a single symbol corresponds to log2(M), where M is the number of points in the constellation, thus 256-QAM transfers 8 bits per symbol. Increasing the number of points in the constellation does not change the bandwidth of the transmission, thus using a modulation scheme with a large number of constellation points, allows for improved spectral efficiency. For example 256-QAM has a spectral efficiency of 8 b/s/Hz, compared with only 1 b/s/Hz for BPSK. However, the greater the number of points in the modulation constellation, the harder they are to resolve at the receiver.

2.5.2. Serial to Parallel and Parallel to Serial Conversion

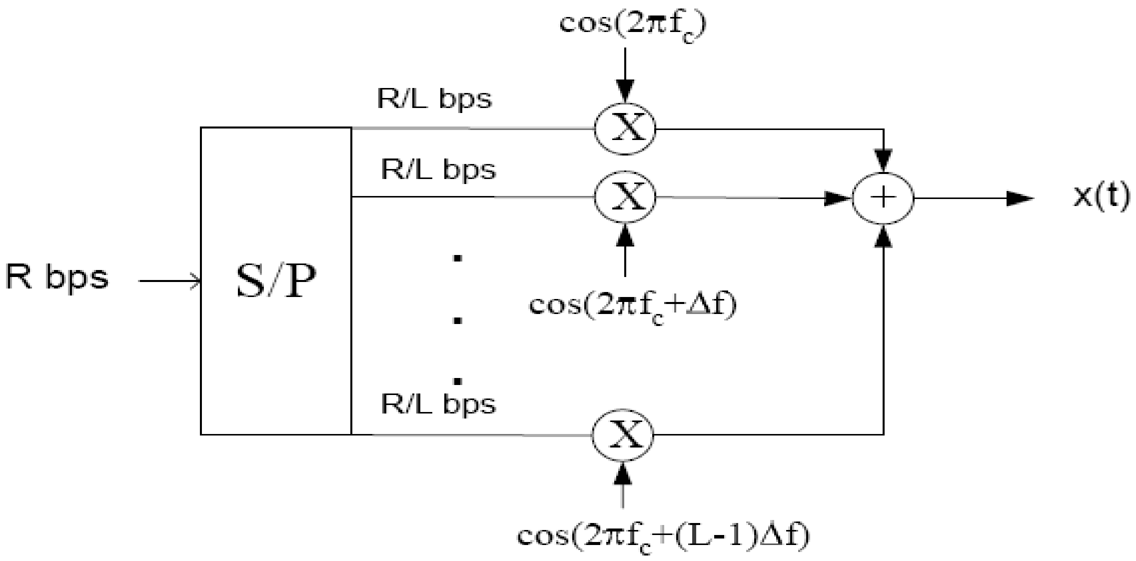


Fig. 2.8 serial to parallel conversion

Data to be transmitted is typically in the form of a serial data stream. In OFDM, each symbol transmits a number of bits and so a serial to parallel conversion stage is needed to convert the input serial bit stream to the data to be transmitted in each OFDM symbol. The data allocated to each symbol depends on the modulation scheme used and the number of subcarriers. At the receiver the reverse process takes place, with the data from the subcarriers being converted back to the original serial data stream.

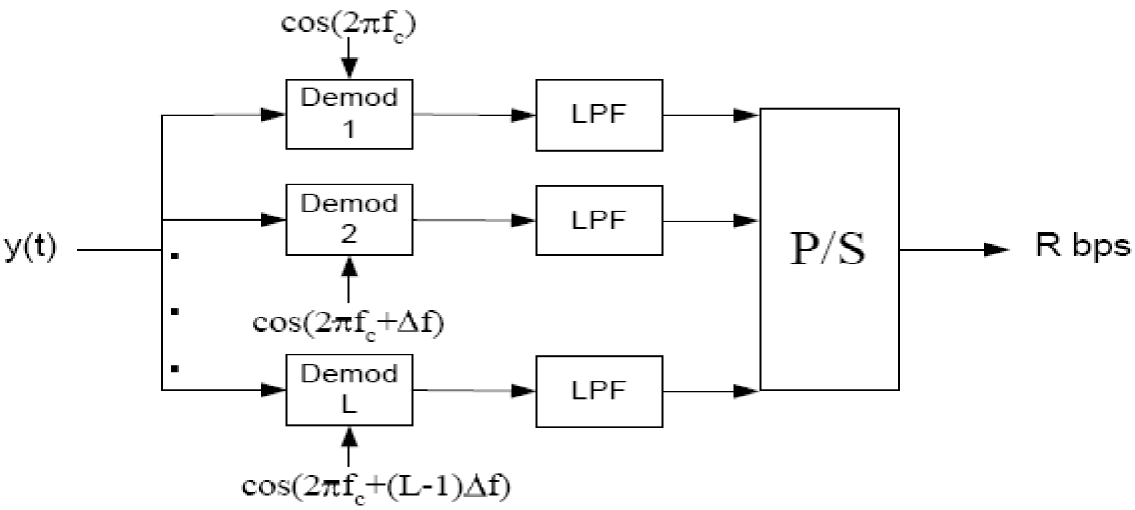


Fig. 2.9 Parallel to serial conversion

2.5.3 Frequency to Time Domain Conversion

The OFDM message is generated in the complex baseband. Each symbol is modulated onto the corresponding subcarrier using variants of phase shift keying (PSK) or different forms of quadrature amplitude modulation (QAM). The data symbols are converted from serial to parallel before data transmission. The frequency spacing between adjacent subcarriers is Nπ/2, where N is the number of subcarriers. This can be achieved by using the inverse discrete Fourier transform (IDFT), easily implemented as the inverse fast Fourier transform (IFFT) operation [6]. As a result, the OFDM symbol generated for an N-subcarrier system translates into N samples, with the ith sample being

$$x_i = \sum_{n=0}^{N-1} C_n \exp\left\{ j\frac{2\pi in}{N} \right\}, \qquad 0 \le i \le N-1 \qquad \text{……………………....2.4}$$

At the receiver, the OFDM message goes through the exact opposite operation in the Fast Fourier transform (FFT) to take the corrupted symbols from a time domain form into the frequency domain. In practice, the baseband OFDM receiver performs the Fast Fourier transform (FFT) of the receive message to recover the information that was originally sent.

2.6 INTERSYMBOL AND INTERCARRIER INTERFERENCE

In a multipath environment, a transmitted symbol takes different times to reach the receiver through different propagation paths. From the receiver's point of view, the channel introduces time dispersion in which the duration of the received symbol is stretched. Extending the symbol duration causes the current received symbol to overlap previous received symbols and results in intersymbol interference (ISI) . In OFDM, ISI usually refers to interference of an OFDM symbol by previous OFDM symbols. For a given system bandwidth the symbol rate for an OFDM signal is much lower than a single carrier transmission scheme. For example for a single carrier BPSK modulation, the symbol rate corresponds to the bit rate of the transmission. However for OFDM the system bandwidth is broken up into N subcarriers, resulting in a symbol rate that is N times lower than the single carrier transmission. This low symbol rate makes OFDM naturally resistant to effects of Inter-Symbol Interference (ISI) caused by multipath propagation. Multipath propagation is caused by the radio transmission signal reflecting off objects in the propagation environment, such as walls, buildings, mountains, etc. These multiple signals arrive at the receiver at different times due to the transmission distances being different. This spreads the symbol boundaries causing energy leakage between them.

In OFDM, the spectra of subcarriers overlap but remain orthogonal to each other. This means that at the maximum of each sub-carrier spectrum, all the spectra of other subcarriers are zero. The receiver samples data symbols on individual sub-carriers at the maximum points and demodulates them free from any interference from the other subcarriers. Interference caused by data symbols on adjacent sub-carriers is referred to intercarrier interference (ICI).

The orthogonality of subcarriers can be viewed in either the time domain or in frequency domain. From the time domain perspective, each subcarrier is a sinusoid with an integer number of cycles within one FFT interval. From the frequency domain perspective, this corresponds to each subcarrier having the maximum value at its own center frequency and zero at the center frequency of each of the other subcarriers. The orthogonality of a subcarrier with respect to other subcarriers is lost if the subcarrier has nonzero spectral value at other subcarrier frequencies. From the time domain perspective, the corresponding sinusoid no longer has an integer number of cycles within the FFT interval. ICI occurs when the multipath channel varies over one OFDM symbol time. When this happens, the Doppler shift on each multipath component causes a frequency offset on the subcarriers, resulting in the loss of orthogonality among them. This situation can be viewed from the time domain perspective, in which the integer number of cycles for each subcarrier within the FFT interval of the current symbol is no longer maintained due to the phase transition introduced by the previous symbol. Finally, any offset between the subcarrier frequencies of the transmitter and receiver also introduces ICI to an OFDM symbol

2.7 GUARD PERIOD

The effect of ISI on an OFDM signal can be further reduced by the addition of a guard period to the start of each symbol. This guard period is a cyclic copy that extends the length of the symbol waveform. Each subcarrier, in the data section of the symbol, (i.e. the OFDM symbol with no guard period added, which is equal to the length of the IFFT size used to generate the signal) has an integer number of cycles. Because of this, placing copies of the symbol end-to-end results in a continuous signal, with no discontinuities at the joins. Thus by copying the end of a symbol and appending this to the start results in a longer symbol time.

Figure 2.10 shows the insertion of a guard period. The total length of the symbol is $TS=TG+TFFT$, where TS is the total length of the symbol in samples, $T G$ is the length of the guard period in samples, and $T FFT$ is the size of the IFFT used to generate the OFDM signal. In addition to protecting the OFDM from ISI, the guard period also provides protection against time-offset errors in the receiver.

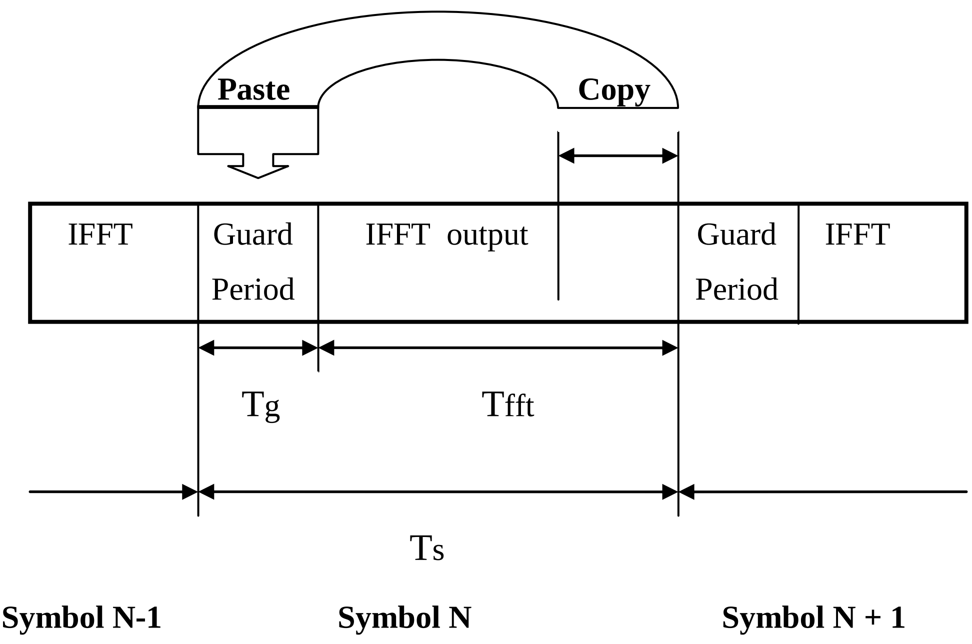


Fig. 2.10 - Guard period insertion in OFDM

- A Guard time is introduced at the end of each OFDM symbol in form of cyclic prefix to prevent Inter Symbol Interference (ISI).
- The Guard time is "cyclically extended" to avoid Inter-Carrier Interference (ICI) - integer number of cycles in the symbol interval.
- Guard Time > Multipath Delay Spread, to guarantee zero ISI & ICI.

2.8 ADDITIVE WHITE GAUSSIAN NOISE (AWGN) CHANNEL

Noise exists in all communications systems operating over an analog physical channel, such as radio. The main sources are thermal background noise, and electrical noise in the receiver amplifiers, and inter-cellular interference. In addition to this noise can also be generated internally to the communications system as a result of Inter-Symbol Interference (ISI), Inter-Carrier Interference (ICI), and Inter- Modulation Distortion (IMD). These sources of noise decrease the Signal to Noise Ratio (SNR), ultimately limiting the spectral efficiency of the system. Noise, in all its forms, is the main detrimental effect in most radio communication systems. It is therefore important to study the effects of noise on the communications error rate and some of the tradeoffs that exists between the level of noise and system spectral efficiency. Most types of noise present in radio communication systems can be modeled accurately using Additive White Gaussian Noise (AWGN). This noise has a uniform spectral density (making it white), and a Gaussian distribution in amplitude (this is also referred to as a normal distribution). Thermal and electrical noise from amplification, primarily have white Gaussian noise properties, allowing them to be modeled accurately with AWGN. Also most other noise sources have AWGN properties due to the transmission being OFDM. OFDM signals have a flat spectral density and a Gaussian amplitude distribution provided that the number of carriers is large (greater than about 20 subcarriers), because of this the inter-cellular interference from other OFDM systems have AWGN properties. For the same reason ICI, ISI, and IMD also have AWGN properties for OFDM signals. In the study of communication systems, the classical (ideal) additive white Gaussian noise (AWGN) channel, with statistically independent Gaussian noise samples corrupting data samples free of intersymbol interference (ISI), is the usual starting point for understanding basic performance relationships. An AWGN channel adds white Gaussian noise to the signal that passes through it.

ADVANTAGES OF OFDM

(i) High spectral efficiency

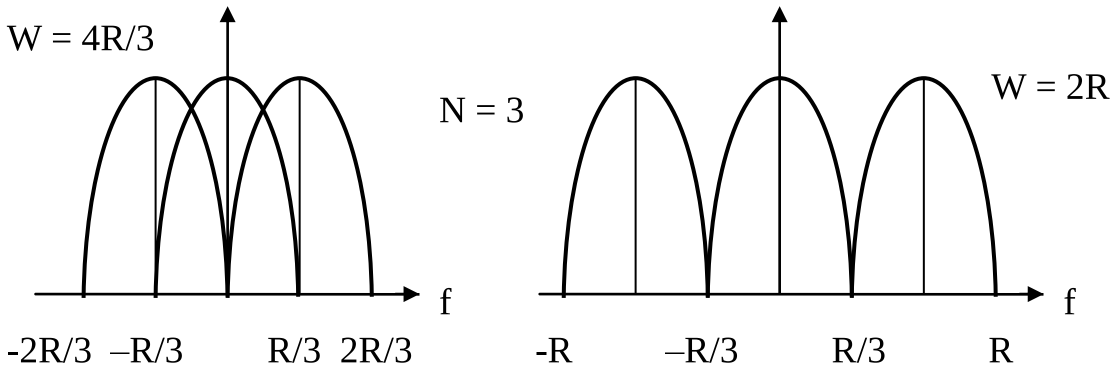


Fig. 2.11 - Spectrum Efficiency of OFDM Compared to FDM

OFDM achieves high spectral efficiency by allowing the sub-carriers to overlap in the frequency domain.

If the number of subcarriers is N and T_s is symbol duration, then total bandwidth required is

$$BW_{total} = \frac{(N+1)}{T_s} \qquad \text{.......................2.5}$$

On the other hand, the bandwidth required for serial transmission of the same data is

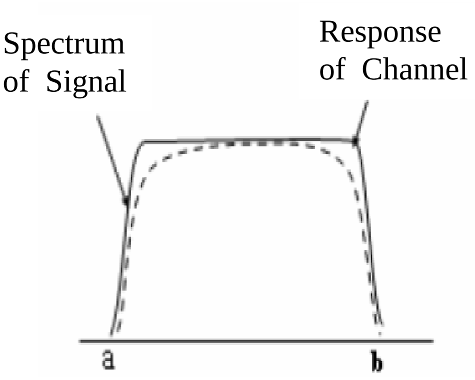
$$BW_{total} = \frac{2N}{T_s} \qquad \text{.......................2.6}$$

(ii) Robustness to Frequency Selective Fading channels

In a multipath channel the reflected signals that are delayed, add to the main signal and cause either gains in the signal strength or loss (deep fade) in the signal strength. Deep fade means the signal is nearly wiped out.

In a channel where deep fades occurs at selected frequencies is called a frequency selective fading channel (Fig. 2.13) & those frequencies depends upon the environment. In a single carrier system the entire signal is lost during the fading intervals.

But as in case of OFDM the signal consists of many sub-carriers, so only few sub-carriers are affected during the fading intervals (Fig. 2.14) & hence a very small percentage of the signal is lost which can be easily recovered.



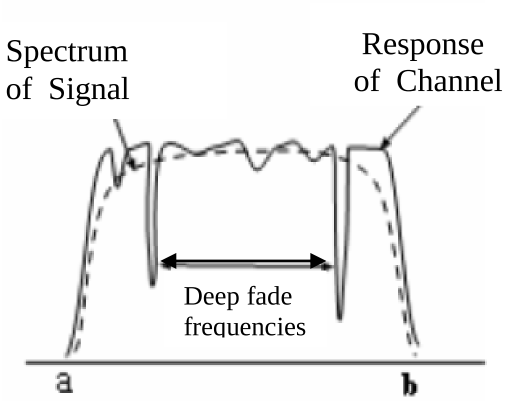


Fig. 2.12 The signal and the channel frequency response. Fig. 2.13 A fading channel frequency response.

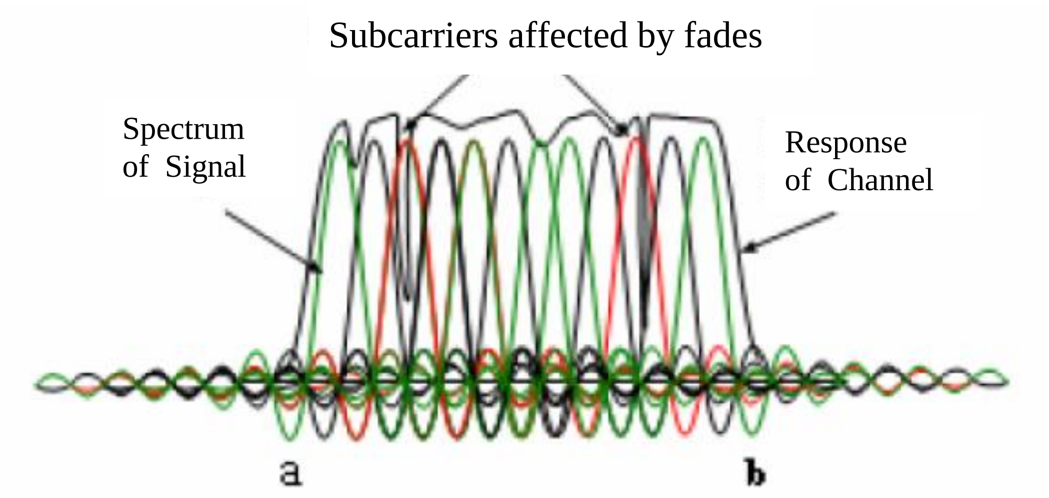


Fig. 2.14 - Robustness of OFDM to Frequency Selective Fading channel

(iii) Multipath Delay Spread Tolerance

OFDM is highly immune to multipath delay spread that causes inter-symbol interference in wireless channels. Since the symbol duration is made larger (by converting a high data rate signal into ‘N’ low rate signals), the effect of delay spread is reduced by the same factor. Also by introducing the concepts of guard time and cyclic extension, the effects of intersymbol interference (ISI) are removed completely.

2.10 ADVANTAGES OF OFDM

- Makes efficient use of the spectrum by allowing overlap.
- By dividing the channel into narrowband flat fading sub channels, OFDM is more resistant to frequency selective fading than single carrier systems are. i.e. robustness to frequency selective fading channels
- Eliminates ISI through use of a cyclic prefix.
- Using adequate channel coding and interleaving one can recover symbols lost due to the frequency selectivity of the channel.
- Channel equalization becomes simpler than by using adaptive equalization techniques with single carrier systems.
- It is possible to use maximum likelihood decoding with reasonable complexity.
- OFDM is computationally efficient by using FFT techniques to implement the modulation and demodulation functions.
- Is less sensitive to sample timing offsets than single carrier systems are.
- Provides good protection against co channel interference and impulsive parasitic noise

2.11 DISADVANTAGES OF OFDM

- It is more sensitive to ICI (inter carrier interference) which is due to frequency offset.
- Peak to average power ratio(PAPR) is high
- Bandwidth and power loss can be significant due to guard interval
- High power transmitter amplifiers need linearization
- Low noise receiver amplifiers need large dynamic range

ICI

Because of the orthogonality of the sub-carriers, we are able to extract the symbols at the receiver as they do not interfere with each other. Orthogonality is preserved as long as sub carriers are harmonics to each other. But at the receiver end, if there is a change of frequency of the sub-carriers due to any reason then the orthogonality among them is lost & ICI occurs. As a result the signal degrades heavily. This change in frequency is called frequency offset. There are two main reasons for frequency offset.

(a) Frequency mismatch between transmitter & receiver

(b) Doppler effect

PAPR

Time domain OFDM signal is a summation of several orthogonal sub-carriers, so OFDM signal has high variation in its envelope. High power transmitter amplifiers need linearization. OFDM signal has a noise like amplitude with a very large dynamic range when passes through RF power amplifiers produces high PAPR. It causes signal distortion. So to reduce PAPR we need linear amplifiers at the transmitter. But linear amplifiers are less efficient and costly compared to non-linear amplifiers.

Guard interval

It is necessary to avoid interference among OFDM symbols but the guard interval consumes 20% of the bandwidth and transmitted power in IEEE 802.11a.

2.12 APPLICATIONS OF OFDM

- Digital Audio Broadcasting (DAB).
- Digital Video Broadcasting (DVB) & HDTV.
- European Wireless LAN Standard – HiperLAN/2
- Used for wideband data communications over mobile radio channels such as
    - High-bit-rate Digital Subscriber Lines (HDSL at 1.6Mbps)
    - Asymmetric Digital Subscriber Lines (ADSL up to 6Mbps)
    - Very-high-speed Digital Subscriber Lines (VDSL at 100 Mbps)
    - ADSL and broadband access via telephone network copper wires.
- IEE 802.11a and 802.11g Wireless LANs.
- The IEEE 802.16 or WiMax Wireless MAN standard.
- The IEEE 802.20 or Mobile Broadband Wireless Access (MBWA) standard.
- The Flash-OFDM cellular system.
- Some Ultra wideband (UWB) systems.
- Power line communication (PLC).
- Point-to-point and point-to-multipoint wireless applications
- OFDM is under consideration for use in 4G Wireless systems

Digital audio broadcasting

DAB was the first commercial use of OFDM technology [5]. Development of DAB started in 1987 and services began in U.K and Sweden in1995. DAB is a replacement for FM audio broadcasting, by providing high quality digital audio and information services. OFDM was used for DAB due to its multipath tolerance. Broadcast systems operate with potentially very long transmission distances (20 -100km). As a result, multipath is a major problem as it causes extensive ghosting of the transmission. This ghosting causes Inter-Symbol Interference (ISI), blurring the time domain signal. For single carrier transmissions the effects of ISI are normally mitigated using adaptive equalization. This process uses adaptive filtering to approximate the impulse response of the radio channel. An inverse channel response filter is then used to recombine the blurred copies of the symbol bits. This process is however complex and slow due to the locking time of the adaptive equalizer. Additionally it becomes increasing difficult to equalize signals that suffer ISI of more than a couple of symbol periods. OFDM overcomes the effects of multipath by breaking the signal into many narrow bandwidth carriers. This results in a low symbol rate reducing the amount of ISI. In addition to this, a guard period is added to the start of each symbol, removing the effects of ISI for multipath signals delayed less than the guard period. The high tolerance to multipath makes OFDM more suited to high data transmissions in terrestrial environments than single carrier transmissions. The data throughput of DAB varies from 0.6 - 1.8 Mbps depending on the amount of Forward Error Correction (FEC) applied. This data payload allows multiple channels to be broadcast as part of the one transmission ensemble. The number of audio channels is variable depending on the quality of the audio and the amount of FEC used to protect the signal. For telephone quality audio (24 kbps) up to 64 audio channels can be provided, while for CD quality audio (256 kb/s), with maximum protection, three channels are available.

The Digital audio broadcasting systems EUREKA 147, Digital Radio Mondiale, HD Radio, T-DMB and ISDB-TSB.

Digital video broadcasting

The development of the Digital Video Broadcasting (DVB) standards was started in 1993. DVB is a transmission scheme based on the MPEG-2 standard, as a method for point to multipoint delivery of high quality compressed digital audio and video. It is an enhanced replacement of the analogue television broadcast standard, as DVB provides a flexible transmission medium for delivery of video, audio and data services [6]. The DVB standards specify the delivery mechanism for a wide range of applications, including satellite TV (DVB-S), cable systems (DVB-C) and terrestrial transmissions (DVB-T). The physical layer of each of these standards is optimized for the transmission channel being used. Satellite broadcasts use a single carrier transmission, with QPSK modulation, which is optimized for this application as a single carrier allows for large Doppler shifts, and QPSK allows for maximum energy efficiency [7]. This transmission method is however unsuitable for terrestrial transmissions as multipath severely degrades the performance of high-speed single carrier transmissions. For this reason, OFDM was used for the terrestrial transmission standard for DVB. The physical layer of the DVB-T transmission is similar to DAB, in that the OFDM transmission uses a large number of subcarriers to mitigate the effects of multipath. DVB-T allows for two transmission modes depending on the number of subcarriers used [8].The major difference between DAB and DVB-T is the larger bandwidth used and the use of higher modulation schemes to achieve a higher data throughput. The DVB-T allows for three subcarrier modulation schemes: QPSK, 16-QAM (Quadrature Amplitude Modulation) and 64- QAM; and a range of guard period lengths and coding rates. This allows the robustness of the transmission link to be traded at the expense of link capacity.

The terrestrial digital TV systems DVB-T, DVB-H, T-DMB and ISDB-T.

Hiperlan2 and IEEE802.11a

Development of the European Hiperlan standard was started in 1995, with the final standard of HiperLAN2 being defined in June 1999. HiperLAN2 pushes the performance of WLAN systems, allowing a data rate of up to 54 Mbps [9]. HiperLAN2 uses 48 data and 4 pilot subcarriers in a 16 MHz channel, with 2 MHz on either side of the signal to allow out of band roll off. User allocation is achieved by using TDM, and subcarriers are allocated using a range of modulation schemes, from BPSK up to 64-QAM, depending on the link quality. Forward Error Correction is used to compensate for frequency selective fading. IEEE802.11a has the same physical layer as HiperLAN2 with the main difference between the standard corresponding to the higher-level network protocols used.HiperLAN2 is used extensively as an example OFDM system in this thesis. Since the physical layer of HiperLAN2 is very similar to the IEEE802.11a standard these examples are applicable to both standards. The most important advantage of the OFDM transmission technique as compared to single carrier systems is obtained in frequency-selective channels. The signal processing in the receiver is rather simple in this case, because after transmission over the radio channel the orthogonality of the OFDM subcarriers is maintained and the channel interference effect is reduced to a multiplication of each subcarrier by a complex transfer factor. Therefore, equalizing the signal is very simple, whereas equalization may not be feasible in the case of conventional single carrier transmission covering the same bandwidth.

Chapter **3**

Digital modulation scheme and radio propogation

DIGITAL MODULATION SCHEME AND RADIO PROPOGATION

3.1 MODULATION

In communication, modulation is the process of varying a periodic waveform, in order to use that signal to convey a message over a medium. Normally a high frequency waveform is used as a carrier signal. The three key parameters of a sine wave are frequency, amplitude, and phase, all of which can be modified in accordance with a low frequency information signal to obtain a modulated signal.

There are 2 types of modulations: Analog modulation and digital modulation. In analog modulation, an information-bearing analog waveform is impressed on the carrier signal for transmission whereas in digital modulation, an information-bearing discrete-time symbol sequence (digital signal) is converted or impressed onto a continuous-time carrier waveform for transmission.

3.2 DIGITAL MODULATION

Nowadays, digital modulation is much popular compared to analog modulation. The move to digital modulation provides more information capacity, compatibility with digital data services, higher data security, better quality communications, and quicker system availability. The aim of digital modulation is to transfer a digital bit stream over an analog band pass channel or a radio frequency band. The changes in the carrier signal are chosen from a finite number of alternative symbols.

Digital modulation schemes have greater capacity to convey large amounts of information than analog modulation schemes.

There are three major classes of digital modulation techniques used for transmission of digitally represented data:

- Amplitude-shift Keying (ASK)
- Frequency-shift keying (FSK)
- Phase-shift keying (PSK)

All convey data by changing some aspect of a base signal, the carrier wave, (usually a sinusoid) in response to a data signal. In the case of PSK, the phase is changed to represent the data signal. There are two fundamental ways of utilizing the phase of a signal in this way:

- By viewing the phase itself as conveying the information, in which case the demodulator must have a reference signal to compare the received signal's phase against; or
- By viewing the *change* in the phase as conveying information — *differential* schemes, some of which do not need a reference carrier (to a certain extent).

A convenient way to represent PSK schemes is on a constellation diagram. This shows the points in the Argand plane where, in this context, the real and imaginary axes are termed the in-phase and quadrature axes respectively due to their 90° separation. Such a representation on perpendicular axes lends itself to straightforward implementation. The amplitude of each point along the in-phase axis is used to modulate a cosine (or sine) wave and the amplitude along the quadrature axis to modulate a sine (or cosine) wave.

3.3 PHASE SHIFT KEYING (PSK)

PSK is a modulation scheme that conveys data by changing, or modulating, the phase of a reference signal (i.e. the phase of the carrier wave is changed to represent the data signal) [24]. A finite number of phases are used to represent digital data. Each of these phases is assigned a unique pattern of binary bits; usually each phase encodes an equal number of bits. Each pattern of bits forms the symbol that is represented by the particular phase.

A convenient way to represent PSK schemes is on a constellation diagram (as shown in figure 3.1 below). This shows the points in the Argand plane where, in this context, the real and imaginary axes are termed the in-phase and quadrature axes respectively due to their 90° separation. Such a representation on perpendicular axes lends itself to straightforward implementation. The amplitude of each point along the in-phase axis is used to modulate a cosine (or sine) wave and the amplitude along the quadrature axis to modulate a sine (or cosine) wave.

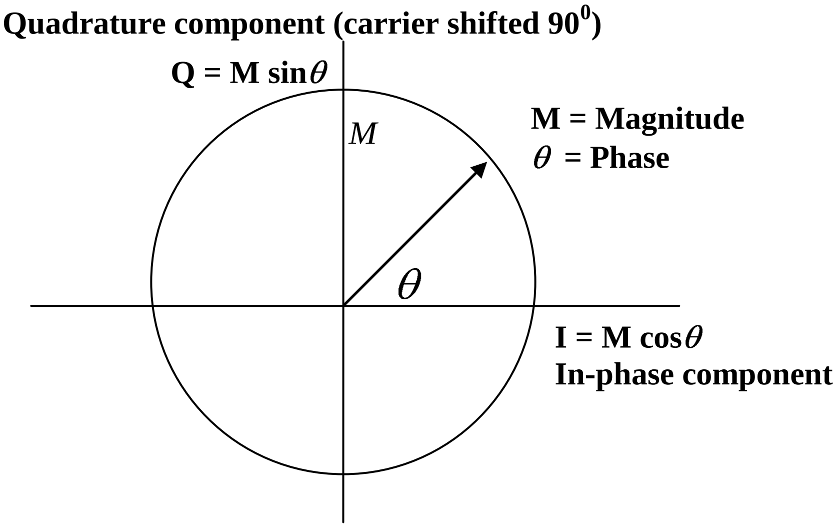


Fig. 3.1- Constellation Diagram

In PSK, the constellation points chosen are usually positioned with uniform angular spacing around a circle. This gives maximum phase-separation between adjacent points and thus the best immunity to corruption. They are positioned on a circle so that they can all be transmitted with the same energy. In this way, the moduli of the complex numbers they represent will be the same and thus so will the amplitudes needed for the cosine and sine waves. Two common examples are binary phase-shift keying (BPSK) which uses two phases, and quadrature phase-shift keying (QPSK) which uses four phases, although any number of phases may be used. Since the data to be conveyed are usually binary, the PSK scheme is usually designed with the number of constellation points being a power of 2. Notably absent from these various schemes is 8-PSK. This is because its error-rate performance is close to that of 16-QAM — it is only about 0.5 dB better— but its data rate is only three-quarters that of 16-QAM. Thus 8-PSK is often omitted from standards and, as seen above, schemes tend to 'jump' from QPSK to 16-QAM (8-QAM is possible but difficult to implement).

Any digital modulation scheme uses a finite number of distinct signals to represent digital data. PSK uses a finite number of phases; each assigned a unique pattern of binary bits. Usually, each phase encodes an equal number of bits. Each pattern of bits forms the symbol that is represented by the particular phase. The demodulator, which is designed specifically for the symbol-set used by the modulator, determines the phase of the received signal and maps it back to the symbol it represents, thus recovering the original data. This requires the receiver to be able to compare the phase of the received signal to a reference signal — such a system is termed coherent (and referred to as CPSK).

Alternatively, instead of using the bit patterns to *set* the phase of the wave, it can instead be used to *change* it by a specified amount. The demodulator then determines the *changes* in the phase of the received signal rather than the phase itself. Since this scheme depends on the difference between successive phases, it is termed differential phase-shift keying (DPSK). DPSK can be significantly simpler to implement than ordinary PSK since there is no need for the demodulator to have a copy of the reference signal to determine the exact phase of the received signal (it is a non-coherent scheme). In exchange, it produces more erroneous demodulations. The exact requirements of the particular scenario under consideration determine which scheme is used.

Applications of PSK

Owing to PSK's simplicity, particularly when compared with its competitor quadrature amplitude modulation, it is widely used in existing technologies.

The wireless LAN standard, IEEE 802.11b-1999, uses a variety of different PSKs depending on the data-rate required. At the basic-rate of 1 Mbit/s, it uses DBPSK (differential BPSK). To provide the extended-rate of 2 Mbit/s, DQPSK is used. In reaching 5.5 Mbit/s and the full-rate of 11 Mbit/s, QPSK is employed, but has to be coupled with complementary code keying. The higher-speed wireless LAN standard, IEEE 802.11g-2003 has eight data rates: 6, 9, 12, 18, 24, 36, 48 and 54 Mbit/s. The 6 and 9 Mbit/s modes use OFDM modulation where each sub-carrier is BPSK modulated. The 12 and 18 Mbit/s modes use OFDM with QPSK. The fastest four modes use OFDM with forms of quadrature amplitude modulation.

Because of its simplicity BPSK is appropriate for low-cost passive transmitters, and is used in RFID standards such as ISO/IEC 14443 which has been adopted for biometric passports, credit cards such as American Express's ExpressPay, and many other applications. IEEE 802.15.4 (the wireless standard used by ZigBee) also relies on PSK. IEEE 802.15.4 allows the use of two frequency bands: 868–915 MHz using BPSK and at 2.4 GHz using OQPSK.

For determining error-rates mathematically, some definitions will be needed:

- E_b = Energy-per-bit
- E_s = Energy-per-symbol = kE_b with k bits per symbol
- T_b = Bit duration
- T_s = Symbol duration
- N_0 / 2 = Noise power spectral density (W/Hz)
- P_b = Probability of bit-error
- P_s = Probability of symbol-error

$Q(x)$ will give the probability that a single sample taken from a random process with zero-mean and unit-variance Gaussian probability density function will be greater or equal to x. It is a scaled form of the complementary Gaussian error function:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2} dt = \frac{1}{2} \operatorname{erfc}\left(\frac{x}{\sqrt{2}}\right), \ x \geq 0 \quad \text{…………………....3.1}$$

The error-rates quoted here are those in additive white Gaussian noise (AWGN). These error rates are lower than those computed in fading channels, hence, are a good theoretical benchmark to compare with. In this project, BPSK, QPSK are selected to be the digital modulation schemes for OFDM. Hence a study on BPSK, QPSK has been carried out.

3.4 BINARY PHASE-SHIFT KEYING (BPSK)

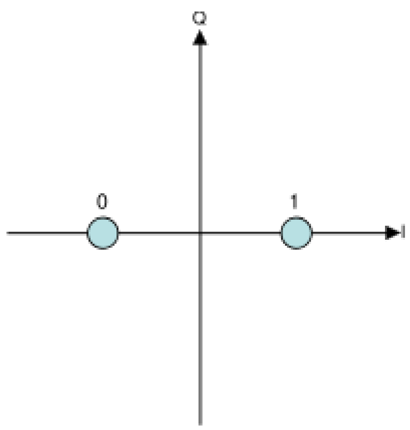


Figure 3.2 Constellation diagram for BPSK.

BPSK (also sometimes called PRK, Phase Reversal Keying) is the simplest form of PSK. It uses two phases which are separated by 180° and so can also be termed 2-PSK. It does not particularly matter exactly where the constellation points are positioned, and in this figure they are shown on the real axis, at 0° and 180°. This modulation is the most robust of all the PSKs since it takes serious distortion to make the demodulator reach an incorrect decision. It is, however, only able to modulate at 1 bit/symbol (as seen in the figure) and so is unsuitable for high data-rate applications when bandwidth is limited. In the presence of an arbitrary phase-shift introduced by the communications channel, the demodulator is unable to tell which constellation point is which. As a result, the data is often differentially encoded prior to modulation.

Binary data is often conveyed with the following signals:

$$s_0(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \pi) = -\sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t)$$ for binary "0" 3.2

$$s_1(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t)$$ for binary "1" …………………….....3.3

Where f_c is the frequency of the carrier-wave. Hence, the signal-space can be represented by the single basis function

$$\phi(t) = \sqrt{\frac{2}{T_b}}\cos(2\pi f_c t)$$ …………………….....3.4

where 1 is represented by $\sqrt{E_b}\phi(t)$ and 0 is represented by $-\sqrt{E_b}\phi(t)$. This assignment is, of course, arbitrary.

Bit error rate

The bit error rate (BER) of BPSK in AWGN can be calculated as:

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$ **Or** $$P_b = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_o}}\right)$$ .....……………3.5

Since there is only one bit per symbol, this is also the symbol error rate.

3.5 QUADRATURE PHASE SHIFT KEYING (QPSK)

QPSK is a multilevel modulation techniques, it uses 2 bits per symbol to represent each phase. Compared to BPSK, it is more spectrally efficient but requires more complex receiver.

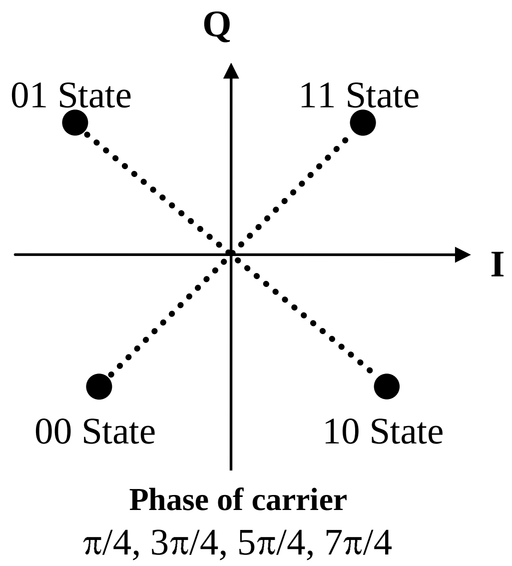


Fig. 3.3- Constellation Diagram for QPSK

Figure 3.3 shows the constellation diagram for QPSK with Gray coding. Each adjacent symbol only differs by one bit. Sometimes known as quaternary or quadriphase PSK or 4-PSK, QPSK uses four points on the constellation diagram, equispaced around a circle. With four phases, QPSK can encode two bits per symbol, shown in the diagram with Gray coding to minimize the BER - twice the rate of BPSK. Analysis shows that QPSK may be used either to double the data rate compared to a BPSK system while maintaining the bandwidth of the signal or to maintain the data-rate of BPSK but halve the bandwidth needed. Although QPSK can be viewed as a quaternary modulation, it is easier to see it as two independently modulated quadrature carriers. With this interpretation, the even (or odd) bits are used to modulate the in-phase component of the carrier, while the odd (or even) bits are used to modulate the quadrature-phase component of the carrier. BPSK is used on both carriers and they can be independently demodulated.

The implementation of QPSK is more general than that of BPSK and also indicates the implementation of higher-order PSK. Writing the symbols in the constellation diagram in terms of the sine and cosine waves used to transmit them:

$$s_i(t) = \sqrt{\frac{2E_s}{T}} \cos\left(2\pi f_c t + (2i-1)\frac{\pi}{4}\right), \quad i = 1, 2, 3, 4. \qquad \text{………….3.6}$$

This yields the four phase's π/4, 3π/4, 5π/4 and 7π/4 as needed.

This results in a two-dimensional signal space with unit basis functions

$$\phi_1(t) = \sqrt{\frac{2}{T_s}} \cos(2\pi f_c t) \qquad \text{……………....3.7}$$

$$\phi_2(t) = \sqrt{\frac{2}{T_s}} \sin(2\pi f_c t) \qquad \text{………………..3.8}$$

The first basis function is used as the in-phase component of the signal and the second as the quadrature component of the signal.

Hence, the signal constellation consists of the signal-space 4 points

$$\left(\pm\sqrt{E_s/2}, \pm\sqrt{E_s/2}\right).$$

The factors of 1/2 indicate that the total power is split equally between the two carriers.

Comparing these basis functions with that for BPSK show clearly how QPSK can be viewed as two independent BPSK signals. Note that the signal-space points for BPSK do not need to split the symbol (bit) energy over the two carriers in the scheme shown in the BPSK constellation diagram.

Bit error rate

Although QPSK can be viewed as a quaternary modulation, it is easier to see it as two independently modulated quadrature carriers. With this interpretation, the even (or odd) bits are used to modulate the in-phase component of the carrier, while the odd (or even) bits are used to modulate the quadrature-phase component of the carrier. BPSK is used on both carriers and they can be independently demodulated.

As a result, the probability of bit-error for QPSK is the same as for BPSK:

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right). \qquad \text{……………....3.9}$$

However, in order to achieve the same bit-error probability as BPSK, QPSK uses twice the power (since two bits are transmitted simultaneously).

The symbol error rate is given by:

$$\begin{aligned} P_s &= 1 - (1 - P_b)^2 \\ &= 2Q\left(\sqrt{\frac{E_s}{N_0}}\right) - Q^2\left(\sqrt{\frac{E_s}{N_0}}\right). \end{aligned}$$

……………….....3.10

If the signal-to-noise ratio is high (as is necessary for practical QPSK systems) the probability of symbol error may be approximated:

$$P_s \approx 2Q\left(\sqrt{\frac{E_s}{N_0}}\right) \qquad \text{………………3.11}$$

QPSK signal in the time domain

The modulated signal is shown below for a short segment of a random binary data-stream. The two carrier waves are a cosine wave and a sine wave, as indicated by the signal-space analysis above. Here, the odd-numbered bits have been assigned to the in-phase component and the even-numbered bits to the quadrature component (taking the first bit as number 1).

The total signal — the sum of the two components — is shown at the bottom. Jumps in phase can be seen as the PSK changes the phase on each component at the start of each bit-period. The topmost waveform alone matches the description given for BPSK above.

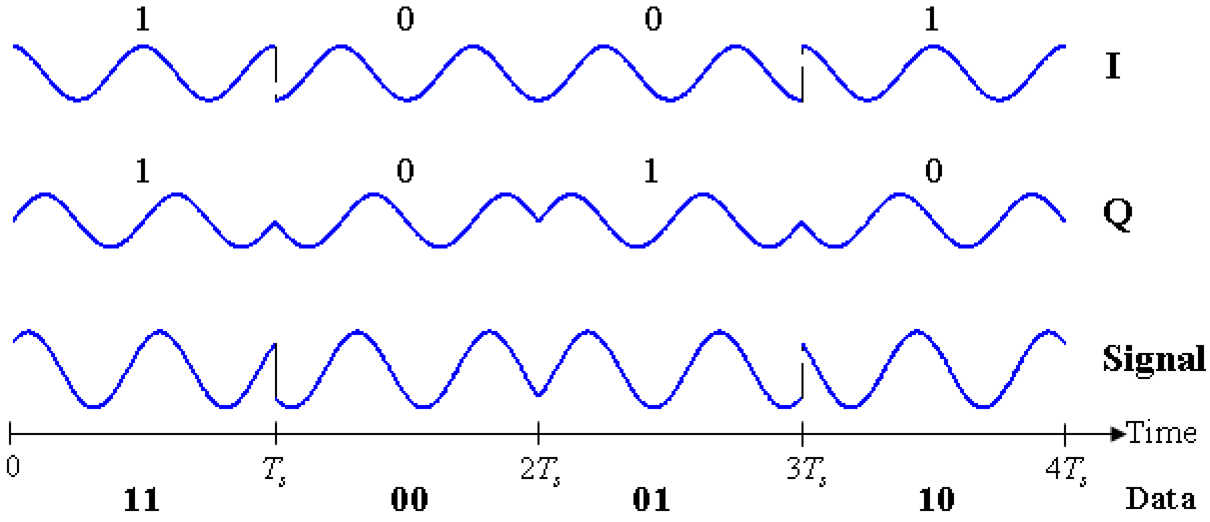


Fig. 3.4 Timing diagram for QPSK.

The binary data stream is shown beneath the time axis. The two signal components with their bit assignments are shown the top and the total, combined signal at the bottom. Note the abrupt changes in phase at some of the bit-period boundaries.

The binary data that is conveyed by this waveform is: 1 1 0 0 0 1 1 0.

- The odd bits, highlighted here, contribute to the in-phase component: **1** 1 **0** 0 **0** 1 **1** 0
- The even bits, highlighted here, contribute to the quadrature-phase component: 1 **1** 0 **0** 0 **1** 1 **0**

3.6 RADIO PROPAGATION

In an ideal radio channel, the received signal would consist of only a single direct path signal, which would be a perfect reconstruction of the transmitted signal. However in a real channel, the signal is modified during transmission in the channel. The received signal consists of a combination of attenuated, reflected, refracted, and diffracted replicas of the transmitted signal [25]. On top of all this, the channel adds noise to the signal and can cause a shift in the carrier frequency if the transmitter or receiver is moving (Doppler Effect). Understanding of these effects on the signal is important because the performance of a radio system is dependent on the radio channel characteristics.

3.6.1 Attenuation

Attenuation is the drop in the signal power when transmitting from one point to another. It can be caused by the transmission path length, obstructions in the signal path, and multipath effects. Any objects that obstruct the line of sight signal from the transmitter to the receiver can cause attenuation. Shadowing of the signal can occur whenever there is an obstruction between the transmitter and receiver. It is generally caused by buildings and hills, and is the most important environmental attenuation factor.

Shadowing is most severe in heavily built up areas, due to the shadowing from buildings. However, hills can cause a large problem due to the large shadow they produce. Radio signals diffract off the boundaries of obstructions, thus preventing total shadowing of the signals behind hills and buildings. However, the amount of diffraction is dependent on the radio frequency used, with low frequencies diffracting more than high frequency signals. Thus high frequency signals, especially, Ultra High Frequencies (UHF), and microwave signals require line of sight for adequate signal strength. To overcome the problem of shadowing, transmitters are usually elevated as high as possible to minimize the number of obstructions.

3.6.2 Fading Effects

Fading is about the phenomenon of loss of signal in telecommunications. Fading or fading channels refers to mathematical models for the distortion that a carrier modulated telecommunication signal experiences over certain propagation media. Small scale fading also known as multipath induced fading is due to multipath propagation. Fading results from the superposition of transmitted signals that have experienced differences in attenuation, delay and phase shift while traveling from the source to the receiver.

3.6.3 Multipath Fading

In wireless communications, multipath is the propagation phenomenon that results on radio signals reaching the receiving antenna by two or more paths. Causes of multipath include atmospheric ducting, ionosphere reflection and refraction and reflection from terrestrial object such as mountains, buildings or vehicles. Figure 3.5 show some of the possible ways in which multipath signals can occur.

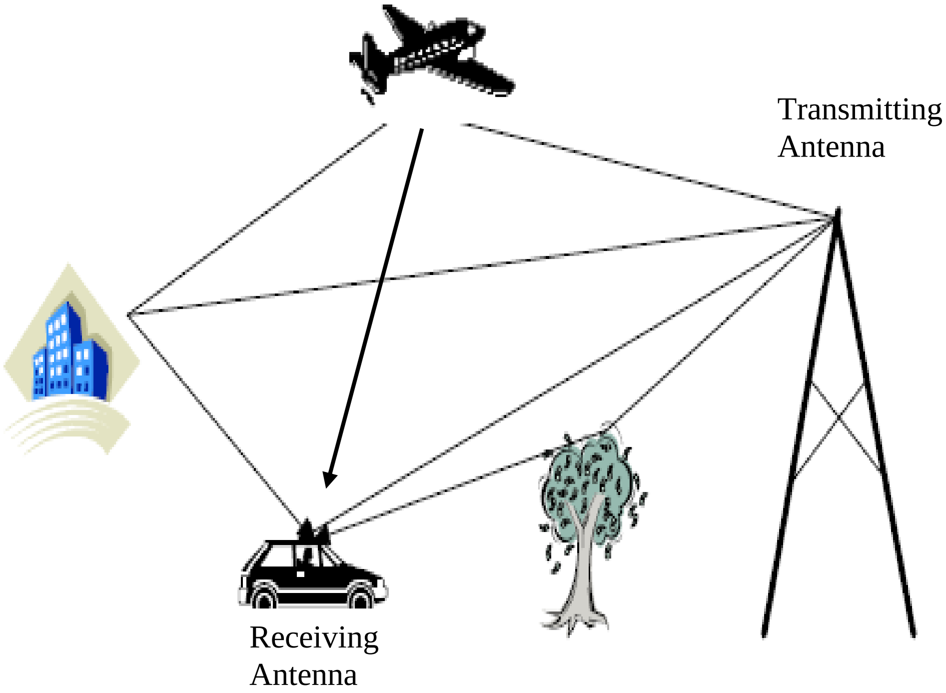


Fig. 3.5- Multipath Signals

The effects of multipath include constructive and destructive interference and phase shifting of the signal which results in Fading of the signal called multipath fading. Small scale fading is usually divided into fading based on multipath time delay spread and that based on Doppler spread.

3.6.4 Delay Spread

The received radio signal from a transmitter consists of typically a direct signal, plus reflections off objects such as buildings, mountains, and other structures. The reflected signals arrive at a later time than the direct signal because of the extra path length, giving rise to a slightly different arrival times, spreading the received energy in time. Delay spread is the time spread between the arrival of the first and last significant multipath signal seen by the receiver. In a digital system, the delay spread can lead to inter-symbol interference. This is due to the delayed multipath signal overlapping with the following symbols. This can cause significant errors in high bit rate systems, especially when using time division multiplexing (TDMA). As the transmitted bit rate is increased the amount of inter-symbol interference also increases. The effect starts to become very significant when the delay spread is greater than ~50% of the bit time.

Inter-symbol interference can be minimized in several ways. One method is to reduce the symbol rate by reducing the data rate for each channel (i.e. split the bandwidth into more channels using frequency division multiplexing, or OFDM). Another is to use a coding scheme that is tolerant to inter-symbol interference such as CDMA. Adding guard interval is also a solution.

There are two type of fading based on multipath time delay spread

- **Flat fading**: the bandwidth of the signal is less than the coherence bandwidth of the channel or the delay spread is less than the symbol period.

- **Frequency selective fading**: the bandwidth of the signal is greater than the coherence bandwidth of the channel or the delay spread is greater than the symbol period.

Frequency selective fading occurs at selected frequencies and those frequencies are determined by the environment. But at these frequencies the signal is almost entirely wiped out. This is because of the destructive interference of the multipath signals.

3.6.5 Doppler Shift

When a wave source and a receiver are moving relative to one another the frequency of the received signal will not be the same as the source. When they are moving toward each other the frequency of the received signal is higher than the source, and when they are moving away each other the frequency decreases. This is called the Doppler Effect. An example of this is the change of pitch in a car's horn as it approaches then passes by. This effect becomes important when developing mobile radio systems.

The amount the frequency changes due to the Doppler Effect depends on the relative motion between the source and receiver and on the speed of propagation of the wave. The Doppler shift in frequency can be written

$$\Delta f = \pm \frac{f v}{c} \cos\theta \qquad \text{.......................3.12}$$

Where Δf is the change in frequency of the source seen at the receiver, f is the frequency of the source, v is the speed difference between the source and receiver, c is the speed of light and θ is the angle between the source and receiver. For example: Let f = 1GHz, and v = 60km/hr (16.67m/s) and θ = 0 degree, then the Doppler shift will be

$$f = 10^9 \cdot \frac{16.67}{3\times10^8} = 55.5\ Hz \qquad \text{.......................3.13}$$

This shift of 55Hz in the carrier will generally not affect the transmission. However, Doppler shift can cause significant problems if the transmission technique is sensitive to carrier frequency offsets (for example OFDM) or the relative speed is very high as is the case for low earth orbiting satellites.

There are two types of fading based on Doppler spread

Fast fading: has a high Doppler spread. The coherence time is less than the symbol time and the channel variations are faster than baseband signal variation.

Slow fading: has a low Doppler spread. The coherence time is greater than the symbol period and the channel variations are slower than the baseband signal variation.

Rayleigh fading

Rayleigh fading is the special case of multipath fading where there is no direct line of sight path available from transmitter to receiver end. That is all the signals received at the receiver are multipath reflected components. The relative phase of multiple reflected signals can cause constructive or destructive interference at the receiver. This is experienced over very short distances (typically at half wavelength distances).

Chapter **4**

methods of ICI reduction

METHODS OF ICI REDUCTION

- Frequency domain equalization
- Time domain windowing
- Pulse shaping
- ICI self cancellation

From the above four methods the first two methods are the initial approach, where as the last two methods are very effective.

4.1 FREQUENCY DOMAIN EQUALIZATION

The fading distortion in the channel causes ICI in the OFDM demodulator. The pattern of ICI varies from frame to frame for the demodulated data but remains invariant for all symbols within a demodulated data frame.

Compensation for fading distortion in the time domain introduces the problem of noise enhancement. So frequency domain equalization process is approached for reduction of ICI by using suitable equalization techniques. We can estimate the ICI for each frame by inserting frequency domain pilot symbols in each frame as shown.

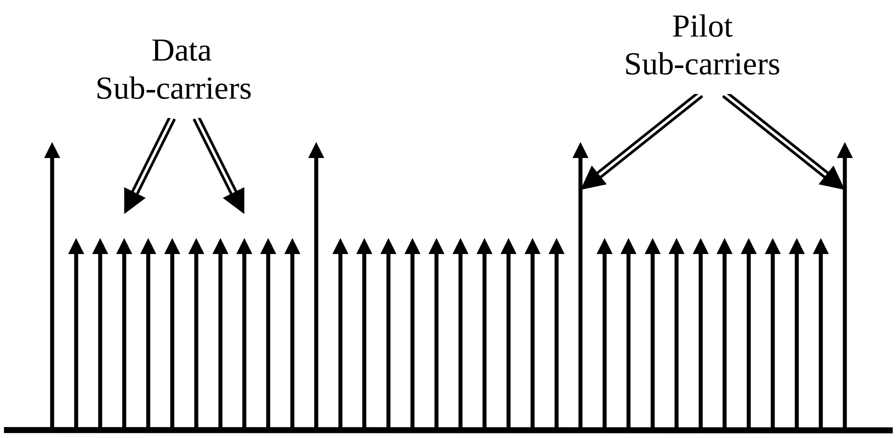


Fig. 4.1- Pilot subcarrier arrangement

The equalizer co-efficient for eliminating ICI in the frequency domain can be derived from the pattern of the pilot symbol & hence a suitable equalizer can be constructed.

Drawbacks

It can only reduce the ICI caused by fading distortion which is not the major source of ICI. The major source of ICI is due to the frequency mismatch between the transmitter and receiver, and the Doppler shift. The above method cannot address to it.

Again it is only suitable for flat fading channels, but in mobile communication the channels are frequency selective fading in nature because of multipath components.

Here also the channel needs to be estimated for every frame. Estimation of channel is complex, expensive & time consuming. Hence the method is not effective one.

4.2 TIME DOMAIN WINDOWING

We know that OFDM signal has widely spread power spectrum. So if this signal is transmitted in a band limited channel, certain portion of the signal spectrum will be cut off, which will lead to inter carrier interference.

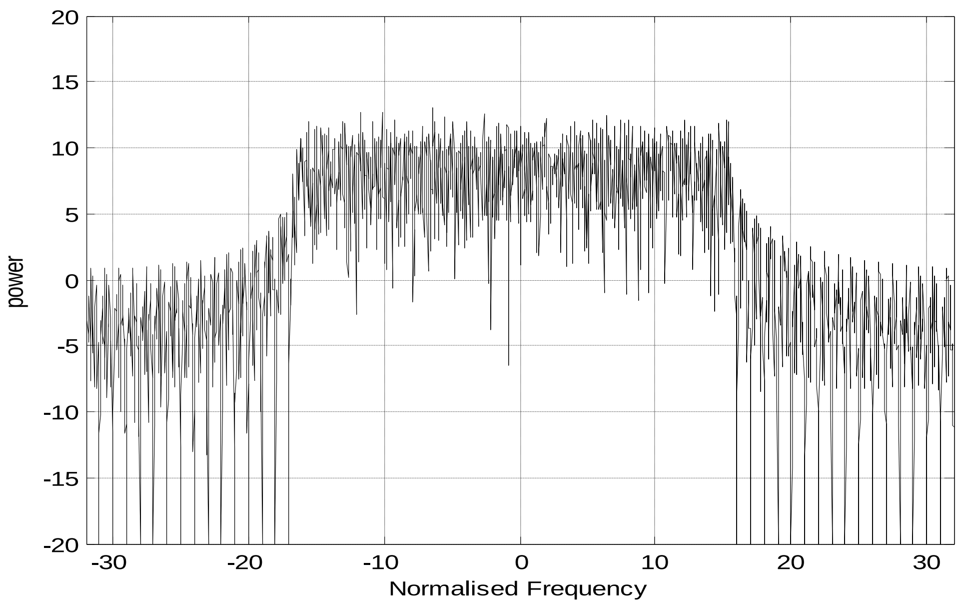


Fig. 4.2- Spectrum of a 64 subcarrier OFDM

To diminish the interference the spectrum of the signal wave form need to be more concentrated. This is achieved by windowing the signal. Basically windowing is the process of multiplying a suitable function to the transmitted signal wave form. The same window is used in the receiver side to get back the original signal.

The IC1 will be eliminated if the product of the window functions satisfies the Nyquist's vestigial symmetry criterion.

Frame by frame windowing

The conventional frame-by-frame time limited orthogonal multicarrier signal S(t) can be expressed as:

$$s(t) = \sum_{k=-\infty}^{\infty} \sum_{n=0}^{N-1} w(t-kT)a_{n,k} \exp(jnw_{\Delta}(t-kT) \qquad \text{.......................4.1}$$

Where $\{a_{n,k}\}$ is a complex sequence, $n\omega_{\Delta}$ $\{n = 0,1,......, N-1\}$ are carrier frequencies and they are equally spaced with ω_{Δ}. The window function w(t) has a length of T and it modifies the waveform of the multicarrier signal in each frame.

The IC1 for this multicarrier signal can be avoided if the window function w(t) and the carrier separation ω_{Δ} are correctly chosen. In order to provide a matched receiver for the transmitted signal, the window functions in both the transmitter and the receiver are selected to be equal. The IC1 can be determined by examining the cross correlation between two carriers of the transmitted signals. For a complex sequence $\{a_{n,k}\}$, the condition for eliminating the IC1 is given by

$$a_{n,k}a_{m,k}^{*} \int_{-T/2}^{T/2} w^{2}(t) \exp(-jw_{\Delta}(n-m)t)dt = 0 \qquad for \ m \neq n \qquad \text{.....................4.2}$$

and if the function $w^2(t)$ meets the Nyquist's vestigial symmetry criterion, this condition will be satisfied. If T' is a time parameter and T/2 ≤ T' ≤ T . Then the window function w(t) which satisfies the Nyquist criterion will be described by

$$w^{2}(t) = \begin{cases} x(t) + y(t) & -T/2 \leq t \leq T/2 \\ 0 & otherwise \end{cases} \qquad \text{.......................4.3}$$

Here x(t) is a rectangular window function over [-T'/2 , T'/2] and y(t) is an even function with odd symmetry about –T'/2 and T'/2 . It is known that the raised cosine function satisfies the *Nyquist* criterion, and so this function can be considered as y(t) .

Here T is defined as T = T' (1+α) and α is the roll-off parameter of the raised cosine function. The IC1 free condition requires the frequency separation between adjacent carriers to be

$$w_{\Delta} = \frac{2\pi(1+\alpha)}{T} \quad \text{.........................4.4}$$

So, the total required bandwidth for N carriers is about $(1+\alpha)/T_S$ where T_S is the symbol interval of the input sequence and $T = NT_S$

Drawbacks

It can only reduce the ICI caused by band limited channel which is not the major source of ICI. The major source of ICI is due to the frequency mismatch between the transmitter and receiver, and the Doppler shift. The above method cannot address to it. Windowing is done frame by frame & hence it reduces the spectral efficiency to a large extent. Hence the method is not effective one.

4.3 PULSE SHAPING

As we have seen in the OFDM spectrum that each carrier consist of a main lobe followed by a number of side lobes with reducing amplitude. As long as orthogonality is maintained there is no interference among the carriers because at the peak of the every carrier, there exist a spectral null. That is at that point the component of all other carriers is zero. Hence the individual carrier is easily separated.

When there is a frequency offset the orthogonality is lost because now the spectral null does not coincide to the peak of the individual carriers. So some power of the side lobes exists at the centre of the individual carriers which is called ICI power. The ICI power will go on increasing as the frequency offset increases. The purpose of pulse shaping is to reduce the side lobes. If we can reduce the side lobe significantly then the ICI power will also be reduced significantly.

Drawback

Complex in implementation

4.3 ICI SELF CANCELLATION

It is seen that the difference between the ICI co-efficient of two consecutive sub-carriers are very small. This makes the basis of ICI self cancellation. Here one data symbol is not modulated in to one sub-carrier, rather at least in to two consecutive sub-carriers. If the data symbol ‘a’ is modulated in to the 1st sub-carrier then ‘-a’ is modulated in to the 2nd sub-carrier. Hence the ICI generated between the two sub-carriers almost mutually cancels each other. This method is suitable for multipath fading channels as here no channel estimation is required. Because in multipath case channel estimation fails as the channel changes randomly.

ICI Cancelling Modulation

In an OFDM communication system, assuming the channel frequency offset normalized by the subcarrier separation is ε , and then the received signal on subcarrier *k* can be written as

$$Y(k) = X(k)S(0) + \sum_{l=0,l\neq k}^{N-1} X(l)S(l-k) + n_k, \qquad k = 0,1,......,\ N-1 \qquad ....4.5$$

Where N is the total number of the subcarriers, X(k) denotes the transmitted symbol for the *k*th subcarrier and n_k is an additive noise sample. The first term in the right-hand side of (4.5) represents the desired signal. The second term is the ICI components. The sequence S(*l*-*k*) is defined as the ICI coefficient between *l*th and *k*th subcarriers, which can be expressed as

$$S(l-k)=\frac{\sin(\pi(l+\varepsilon-k))}{N\sin\left(\frac{\pi}{N}(l+\varepsilon-k)\right)}.\exp\left(j\pi\left(1-\frac{1}{N}\right)(l+\varepsilon-k)\right) \qquad \text{.......................4.6}$$

It is seen that the difference of ICI coefficient between two consecutive subcarrier {(S(*l*-*k*) and S(*l*+1-*k*)} is very small. Therefore, if a data pair (a, -a) is modulated onto two adjacent subcarriers (*l* , *l*+1), where *a* is a complex data, then the ICI signals generated by the subcarrier *l* will be cancelled out significantly by the ICI generated by subcarrier *l*+1 .

Assuming the transmitted symbols are such that
X(1) = -X(0), X(3) = -X(2),…….., X(N-1) = -X(N-2), then the received signal on subcarrier *k* becomes

$$Y'(k)=\sum_{\substack{l=0\\ l=even}}^{N-2} X(l)[S(l-k)-S(l+1-k)]+n_k \qquad \text{.......................4.7}$$

Similarly the received signal on subcarrier *k*+1 becomes

$$Y'(k+1)=\sum_{\substack{l=0\\ l=even}}^{N-2} X(l)[S(l-k-1)-S(l-k)]+n_{k+1} \qquad \text{.......................4.8}$$

In such a case, the ICI coefficient is denoted as

$$S'(l-k)=S(l-k)-S(l+1-k) \qquad \text{.......................4.9}$$

It is found that $S'(l-k)<<S(l-k)$, which is shown in figure 4.3

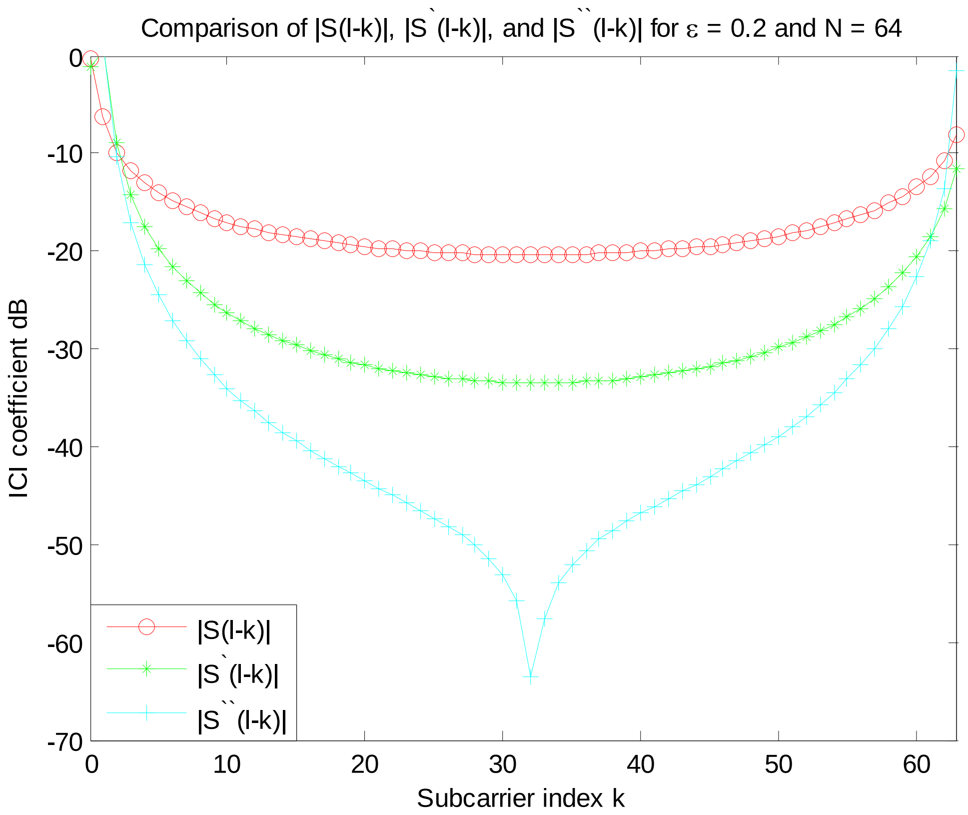


Fig. 4.3 - Comparison between $|S(l-k)|$, $|S'(l-k)|$ and $|S''(l-k)|$

ICI Cancelling Demodulation

To further reduce ICI, ICI cancelling demodulation is done. The demodulation is suggested to work in such a way that each signal at the k+1th subcarrier (now k denotes even number) is multiplied by " -1" and then summed with the one at the kth subcarrier. Then the resultant data sequence is used for making symbol decision. It can be represented as

$$
\begin{aligned}
Y''(k) &= Y'(k) - Y'(k+1) \\
&= \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[-S(l-k-1) + 2S(l-k) - S(l-k+1)] + n_k - n_{k+1} \quad \text{.....................4.10}
\end{aligned}
$$

The corresponding ICI coefficient then becomes

$$S''(l-k) = -S(l-k-1) + 2S(l-k) - S(l-k+1) \quad \text{.........................4.11}$$

Figure 4.3 shows the amplitude comparison of $|S(l-k)|$, $|S'(l-k)|$ and $|S''(l-k)|$ for N = 64 and ε = 0.3. For the majority of (*l*-*k*) values, $|S'(l-k)|$ is much smaller than $|S(l-k)|$, and the $|S''(l-k)|$ is even smaller than $|S'(l-k)|$.

Thus, the ICI signals become smaller when applying ICI cancelling modulation. On the other hand, the ICI canceling demodulation can further reduce the residual ICI in the received signals.

The combined ICI cancelling modulation and demodulation method is called the ICI self-cancellation scheme.

Drawback

The major drawback of this method is the reduction in band width efficiency as same symbol occupies two sub-carriers.

Merits of this technique

1.

1. It is suitable for multipath fading channels
2. It is also suitable for flat channels
3. Channel estimation is not required
4. Channel equalization is not required
5. It is simple in implementation
6. It is less complex and effective

Chapter **5**

ICI reduction using self cancellation scheme

ICI REDUCTION USING SELF CANCELLATION

5.1 SYSTEM MODEL

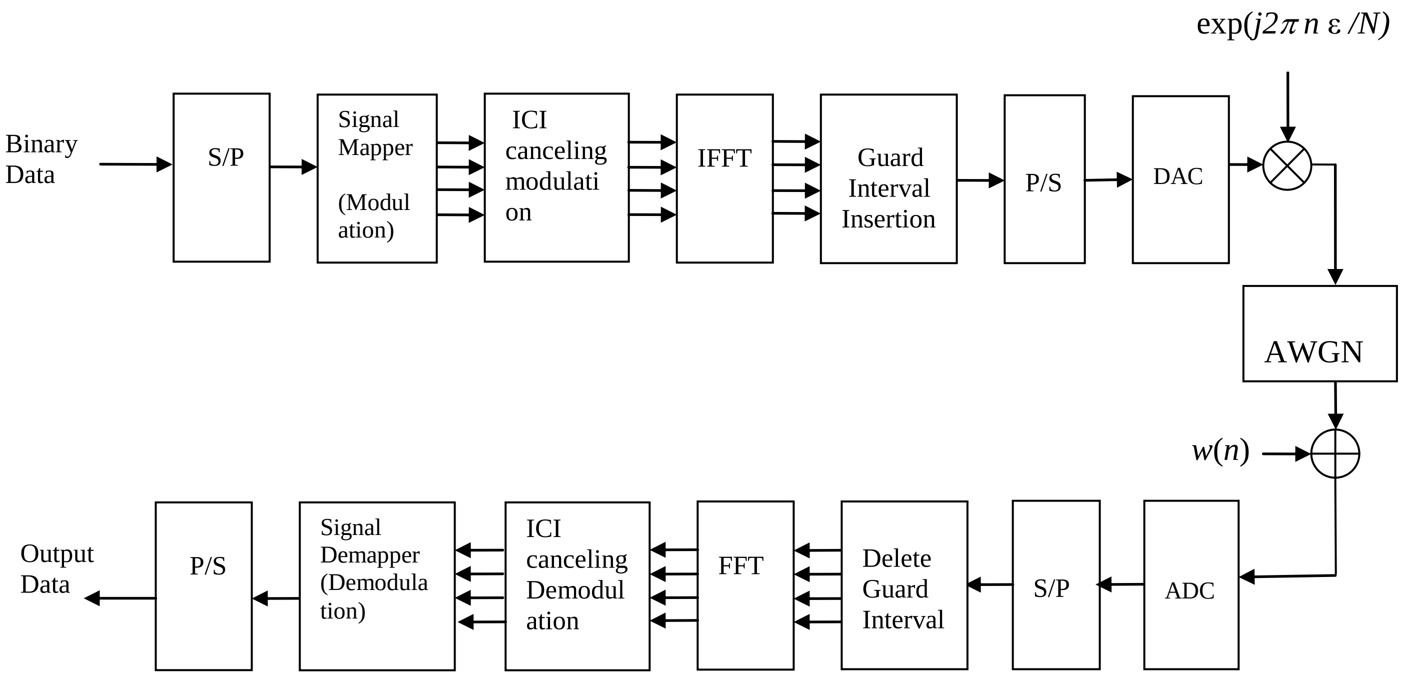


Fig. 5.1 N –subcarrier OFDM system model

The high data rate serial input bit stream is fed into serial to parallel converter to get low data rate output parallel bit stream. Input bit stream is taken as binary data. The low data rate parallel bit stream is modulated in Signal Mapper. Modulation can be BPSK, QPSK, etc.

The modulated data are served as input to ICI canceling modulation. ICI coefficients can be found in this. The OFDM symbols are fed to Inverse Fast Fourier transform so that each subcarrier is assigned with a specific frequency. The frequencies are selected so that they are orthogonal in nature. In this block, orthogonality in subcarriers is introduced. In IFFT, the frequency domain OFDM symbols are converted into time domain OFDM symbols. After this, Guard interval is inserted in each OFDM symbol to eliminate inter symbol interference (ISI). All the OFDM symbols are taken as input to parallel to serial block. These OFDM symbols constitute a frame. A number of frames can be regarded as one OFDM signal. This OFDM signal is allowed to pass through digital to analog converter (DAC). In DAC the OFDM signal is fed to RF power amplifier for transmission. If there is frequency mismatch between transmitter and receiver local oscillators frequency offset occurs. Doppler shift also introduces frequency offset. This frequency offset (ε) occurs in OFDM signal due to these reasons. Then the signal is allowed to pass through additive white Gaussian noise channel (AWGN channel). At the receiver part, the received OFDM signal is fed to analog to digital converter (ADC) and is taken as input to serial to parallel converter. In these parallel OFDM symbols, Guard interval is removed and it is allowed to pass through Fast Fourier transform. Here the time domain OFDM symbols are converted into frequency domain. ICI canceling demodulation is performed on these OFDM symbols. ICI canceling modulation and ICI canceling demodulation together known as ICI Self Cancellation. After this it is fed into Signal Demapper for demodulation purpose. And finally the low data rate parallel bit stream is converted into high data rate serial bit stream.

5.2 ANALYSIS OF INTER-CARRIER INTERFERENCE

The main disadvantage of OFDM, however, is its susceptibility to small differences in frequency at the transmitter and receiver, normally referred to as frequency offset. This frequency offset can be caused by Doppler shift due to relative motion between the transmitter and receiver, or by differences between the frequencies of the local oscillators at the transmitter and receiver. In this project, the frequency offset is modeled as a multiplicative factor introduced in the channel, as shown in Figure 5.1

The received signal is given by,

$$y(n) = x(n)e^{j2\pi n\frac{\varepsilon}{N}} + w(n) \qquad \text{………………….....5.1}$$

where ε represents the normalized frequency offset, that is, $\varepsilon = \Delta f\ /(1/NT)$, where Δf is the frequency difference between the transmitter and the receiver, and *NT* denotes the interval of an FFT period [26]. w(n) is the AWGN introduced in the channel and T is the subcarrier symbol period.

ICI mechanism of standard OFDM systems

The effect of the channel frequency offset on the received symbol stream can be understood by considering the received symbol Y(k) on the k^{th} sub-carrier. In an OFDM communication system, assume the channel frequency offset normalized by the subcarrier separation is ε, the received signal on subcarrier k can be written as

$$Y(k) = X(k)S(0) + \sum_{l=0, l \neq k}^{N-1} X(l)S(l-k) + n_k \qquad \text{……………....5.2}$$
$$k = 0,1,2,\ldots\ldots N-1$$

Where N is the total number of the subcarriers, $X(k)$ denotes the transmitted symbol (-ary phase-shift keying (PSK), for example) for the kth subcarrier and n_k is an additive noise sample. The ICI components are the interfering signals transmitted on sub-carriers other than the k^{th} sub-carrier. $S(l\text{-}k)$ are the complex coefficients for the ICI components in the received signal. The sequence $S(l\text{-}k)$ is defined as the ICI coefficient between lth and kth subcarriers, which can be expressed as

$$S(l-k) = \frac{\sin(\pi(l+\varepsilon-k))}{N\sin(\pi(l+\varepsilon-k)/N)}\exp(j\pi(1-\frac{1}{N})(l+\varepsilon-k)) \qquad \text{…..………..5.3}$$

where ε represents the normalized frequency offset, that is, $\varepsilon = \Delta f/(1/NT)$, where Δf is the frequency difference between the transmitter and the receiver, and NT denotes the interval of an FFT period . The first term in the right-hand side of (5.2) represents the desired signal. The second term is the ICI components.

The self cancellation method relies on the fact that the real and imaginary parts of the ICI coefficients change gradually with respect to the subcarrier index k; therefore, the difference between consecutive ICI coefficients, $S(l\text{-}k)\text{-}S(l\text{-}k+1)$, is very small. The system ICI power level can be evaluated by using the CIR [2]. While deriving the theoretical CIR expression, the additive noise is omitted.

During modulation, one data symbol is mapped onto two consecutive subcarriers with predefined weighting coefficients. The weighting coefficients are calculated carefully such that the ICI signals within the successive subcarriers are cancelled by each other at the receiver end; hence this technique is called “self-cancellation”. It is worth noting that the redundant modulation in the self-cancellation scheme reduces the bandwidth efficiency. The investigators will explore ways to compensate for that problem if possible. With this scheme, carrier-to-interference ratio (CIR) will increase, thus improving the bit error rate (BER) at the receiver. The goal in this part of the project is to simulate different OFDM channels and use the self-cancellation scheme to determine and compare the improvements in the CIR and BER. To analyze the effect of ICI on the received signal, we consider a system with N=16 carriers. The frequency offset values used are 0.2 and 0.4, and l is taken as 0, that is, we are analyzing the signal received at the sub-carrier with index 0. The complex ICI coefficients S(l-k) are plotted for all sub-carrier indices in Figure 5.2

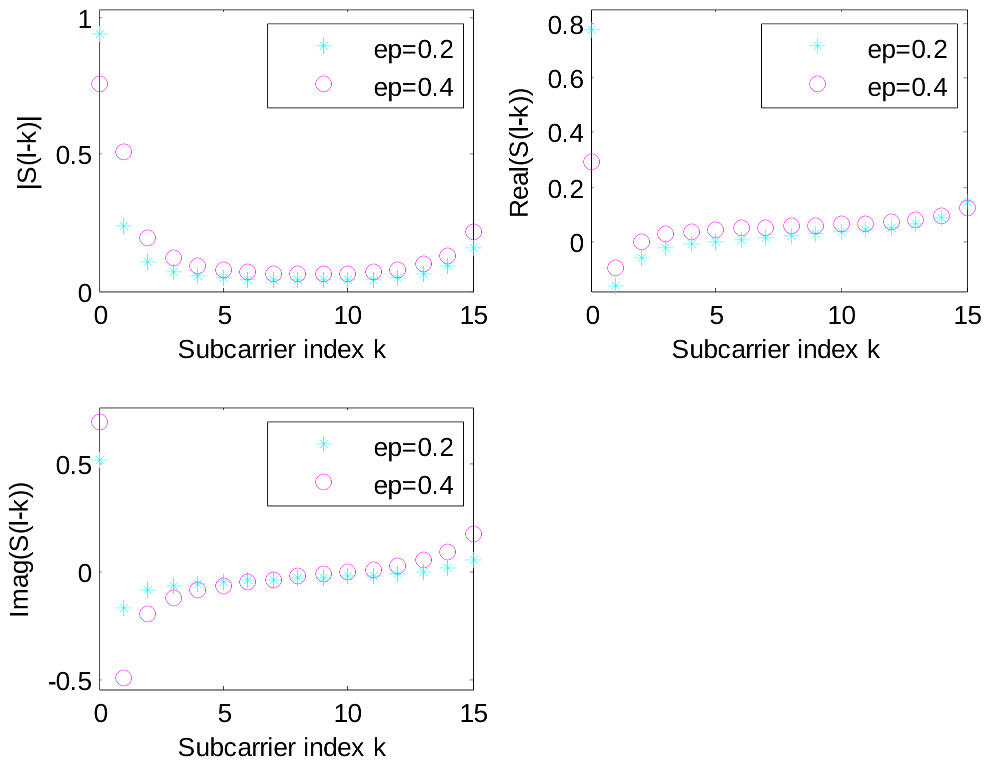


Figure 5.2

An example of $S(l - k)$ for $N = 16$; $l = 0$. (a) Amplitude of $S(l - k)$.

An example of $S(l - k)$ for $N = 16$; $l = 0$. (b) Real part of $S(l-k)$.

An example of $S(l - k)$ for $N = 16$; $l = 0$. (c) Imaginary part of $S(l-k)$.

The figure 5.2 shows that for a larger ε, the weight of the desired signal component, S(0), decreases, while the weights of the ICI components increases. We can notice that the adjacent carrier has the maximum contribution to the ICI. This fact is used in the ICI self-cancellation technique.

The carrier-to-interference ratio (CIR) is the ratio of the signal power to the power in the interference components. It serves as a good indication of signal quality. It has been derived from $Y(k)$ equation and is given below. The derivation assumes that the standard transmitted data has zero mean and the symbols transmitted on the different sub-carriers are statistically independent. In deriving the theoretical CIR expression, the additive noise is omitted. The desired received signal power on the k th sub carrier can be represented as

$$\mathrm{E}\left[\left|C(k)\right|^2\right] = \mathrm{E}\left[\left|X(k)S(0)\right|^2\right] \qquad \text{.........................5.4}$$

The ICI power is represented as

E [redacted] $(k)|^2 = \mathrm{E}\left[\left|\sum_{l=0,l\neq k}^{N-1} X(l)S(l-k)\right|^2\right] \qquad \text{.........................5.5}$

CIR is given by below equation

$$CIR = \frac{S(k)^2}{\sum_{l=0,l\neq k}^{N-1} S(l-k)^2} = \frac{\left|S(0)^2\right|}{\sum_{l=1}^{N-1} S(l)^2} \qquad \text{.........................5.6}$$

The carrier-to-interference power ratio (CIR) can be increased by 15 and 30 dB when the group size is two or three, respectively, for a channel with a constant frequency offset.

ICI self-cancellation[15] is a scheme that was introduced by Yuping Zhao and Sven-Gustav Häggman in 2001 to combat and suppress ICI in OFDM. Succinctly, the main idea is to modulate the input data symbol onto a group of subcarriers with predefined coefficients such that the generated ICI signals within that group cancel each other, hence the name self-cancellation.

5.3 ICI CANCELING MODULATION

The ICI self-cancellation scheme [26] requires that the transmitted signals be constrained such that

X(1) = -X(0), X(3) = -X(2),…….., X(N-1) = -X(N-2),

Using (5.3), this assignment of transmitted symbols allows the received signal on subcarriers k and k + 1 to be written as

$$Y'(k) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[S(l-k) - S(l+1-k)] + n_k \qquad \text{…………….....5.7}$$

$$Y'(k+1) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[S(l-k-1) - S(l-k)] + n_{k+1} \qquad \text{…………….....5.8}$$

and the ICI coefficient S'(l-k) is denoted as[15]

$$S'(l-k) = S(l-k) - S(l+1-k) \qquad \text{…………………......5.9}$$

Figure 5.3 shows a comparison between |S'(l-k)| and |S(l-k)| on a logarithmic scale. It is seen that |S'(l-k)| << |S(l-k)| for most of the l-k values. Hence, the ICI components are much smaller in (5.9) than they are in (5.3). Also, the total number of interference signals is halved in (5.9) as opposed to (5.3) since only the even subcarriers are involved in the summation.

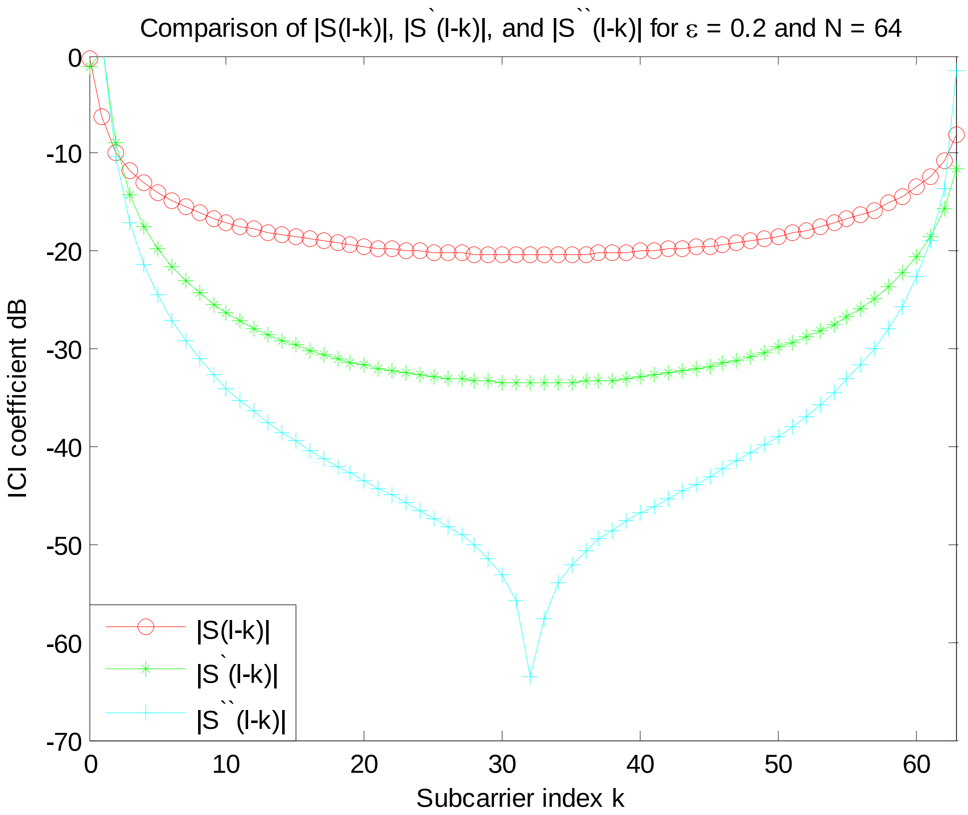


Fig. 5.3 comparison of |S(l-k)|, |S'(l-k)|, |S''(l-k)|

5.4 ICI CANCELLING DEMODULATION

ICI modulation introduces redundancy in the received signal since each pair of subcarriers transmit only one data symbol. This redundancy can be exploited to improve the system power performance, while it surely decreases the bandwidth efficiency. To take advantage of this redundancy, the received signal at the $(k + 1)^{th}$ subcarrier, where k is even, is subtracted from the k^{th} subcarrier. This is expressed mathematically as

$$Y''(k) = Y'(k) - Y'(k+1)$$
$$= \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)[-S(l-k-1) + 2S(l-k) - S(l-k+1)] + n_k - n_{k+1} \quad \text{.................5.10}$$

Subsequently, the ICI coefficients for this received signal becomes

$$S''(l-k) = -S(l-k-1) + 2S(l-k) - S(l-k+1) \qquad \text{.................5.11}$$

When compared to the two previous ICI coefficients |S(l-k)| for the standard OFDM system and |S'(l-k)| for the ICI canceling modulation, |S''(l-k)| has the smallest ICI coefficients, for the majority of l-k values, followed by |S'(l-k)| and |S(l-k)|. This is shown in Figure 5.3 for N = 64 and ε = 0.4. The combined modulation and demodulation method is called the ICI self-cancellation scheme. The reduction of the ICI signal levels in the ICI self-cancellation scheme [26] leads to a higher CIR.

From (5.11), the theoretical CIR can be derived as

$$CIR = \frac{\left|-S(-1) + 2S(0) - S(1)\right|^2}{\sum_{l=2,4,6,....}^{N-1} \left|-S(l-1) + 2S(l) - S(l+1)\right|^2} \qquad \text{.......................5.12}$$

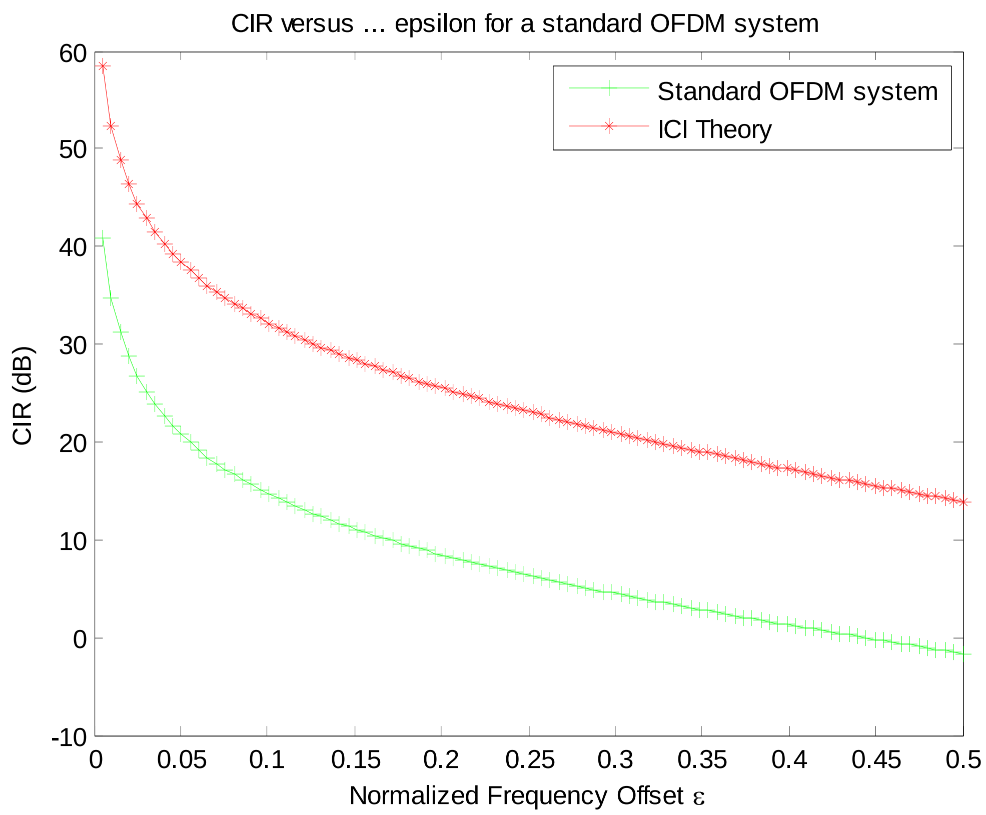


Fig. 5.4 CIR versus ε for a standard OFDM system and ICI theory

Figure 5.4 above shows the comparison of the theoretical CIR curve of the ICI self-cancellation scheme, calculated by (5.12), and the CIR of a standard OFDM system calculated by (5.3). As expected, the CIR is greatly improved using the ICI self-cancellation scheme. The improvement can be greater than 15 dB for $0 < \varepsilon < 0.5$.

As mentioned above, the redundancy in this scheme reduces the bandwidth efficiency by half. This could be compensated by transmitting signals of larger alphabet size. Using the theoretical results for the improvement of the CIR should increase the power efficiency in the system and gives better results for the BER. Hence, there is a tradeoff between bandwidth and power in the ICI self-cancellation scheme.

Chapter **6**

simulation results

SIMULATION RESULTS AND DISCUSSION

6.1 OFDM MODEL USED FOR SIMULATION

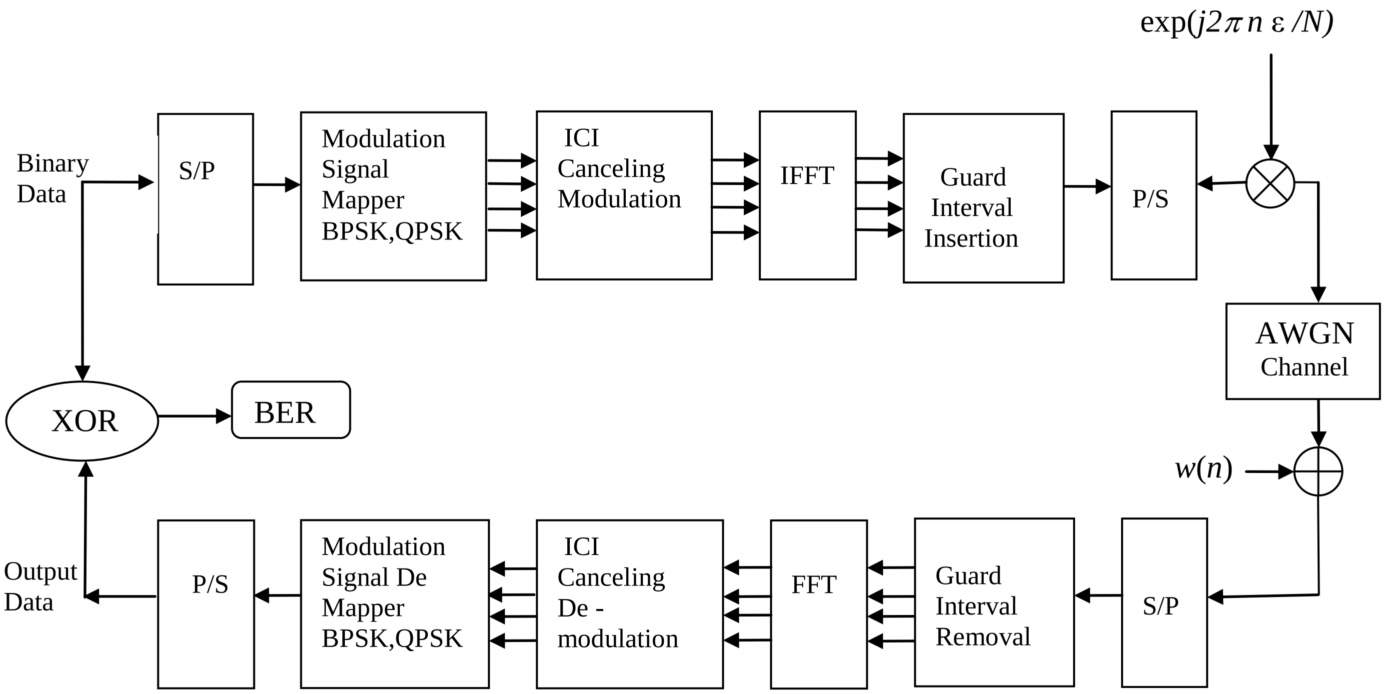


Fig. 6.1 – OFDM Model used for Simulation

Figure 6.1 shows the Fast Fourier transform (FFT) based *N*-subcarrier OFDM system model used for simulation. The simulation parameters used for the above model is as given below.

Parameter	**Specifications**
IFFT Size	64
Number of Carriers in one OFDM symbol	52
Channel	AWGN
Frequency Offset	0, 0.15, 0.3
Guard Interval	12
Modulation	BPSK,QPSK
OFDM symbols for one loop	10000

Table 6.1- Simulation Parameters

6.2 BER performance of BPSK OFDM system

(a) BER performance of a standard BPSK OFDM system

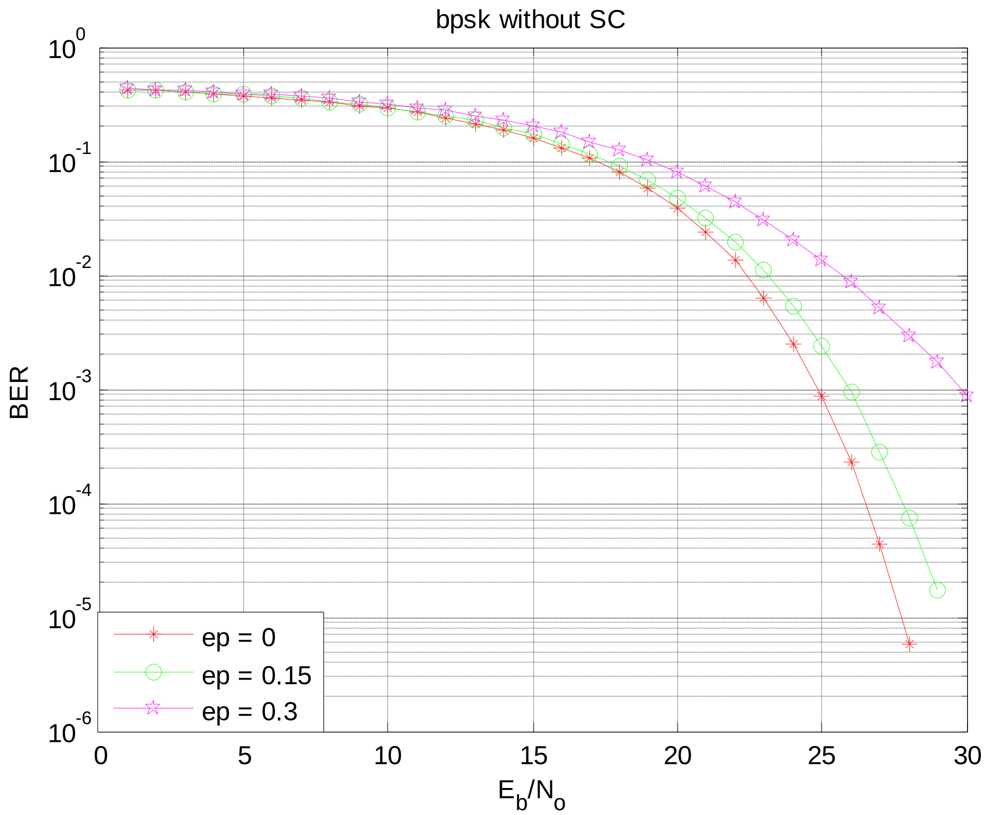


Fig. 6.2 BER performance of a standard BPSK OFDM system

Here the plot shows BER vs SNR for BPSK without self cancellation for different values of carrier frequency offset. From the figure we observe that as the value of carrier frequency offset ε increases, the BER increases. As SNR increases BPSK BER curve leans downward which indicates reduction in bit error rate.

(b) BER performance of a BPSK OFDM system with Self Cancellation

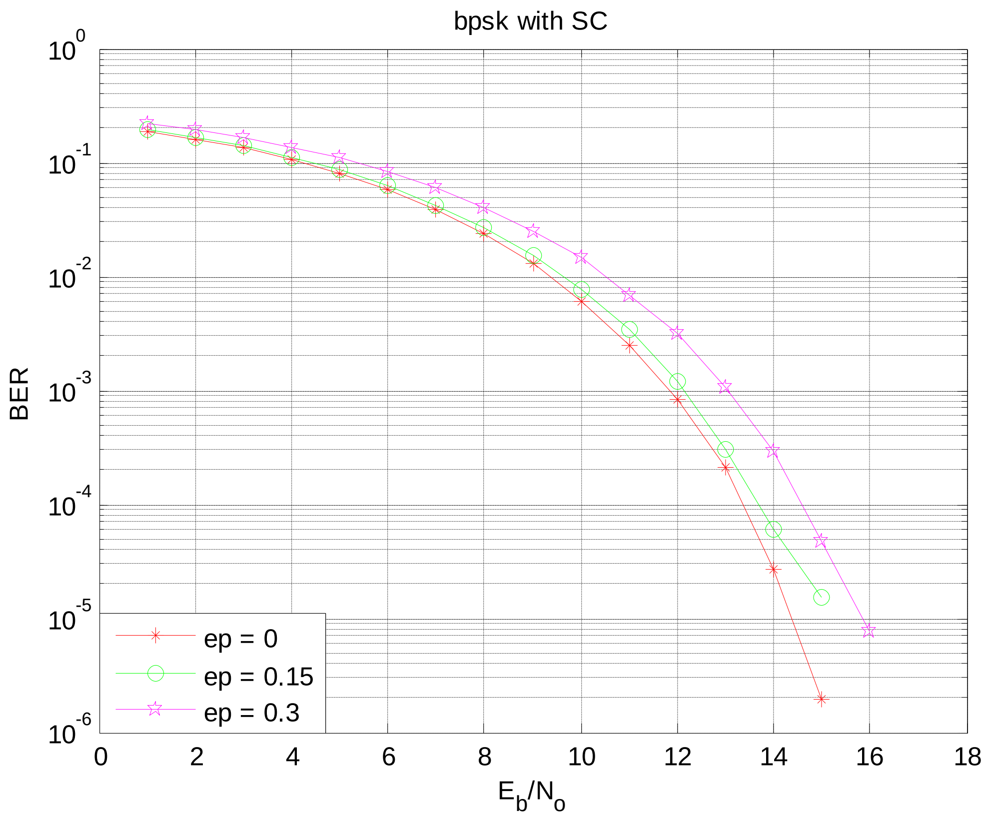


Fig. 6.3 BER performance of a BPSK OFDM system with Self Cancellation

From the figure we can infer that as the value of carrier frequency offset ε increases, the BER increases. As SNR increases BER curve of BPSK with self cancellation tends downward which indicates reduction in bit error rate.

(c) BER performance of a BPSK OFDM system with & without Self Cancellation

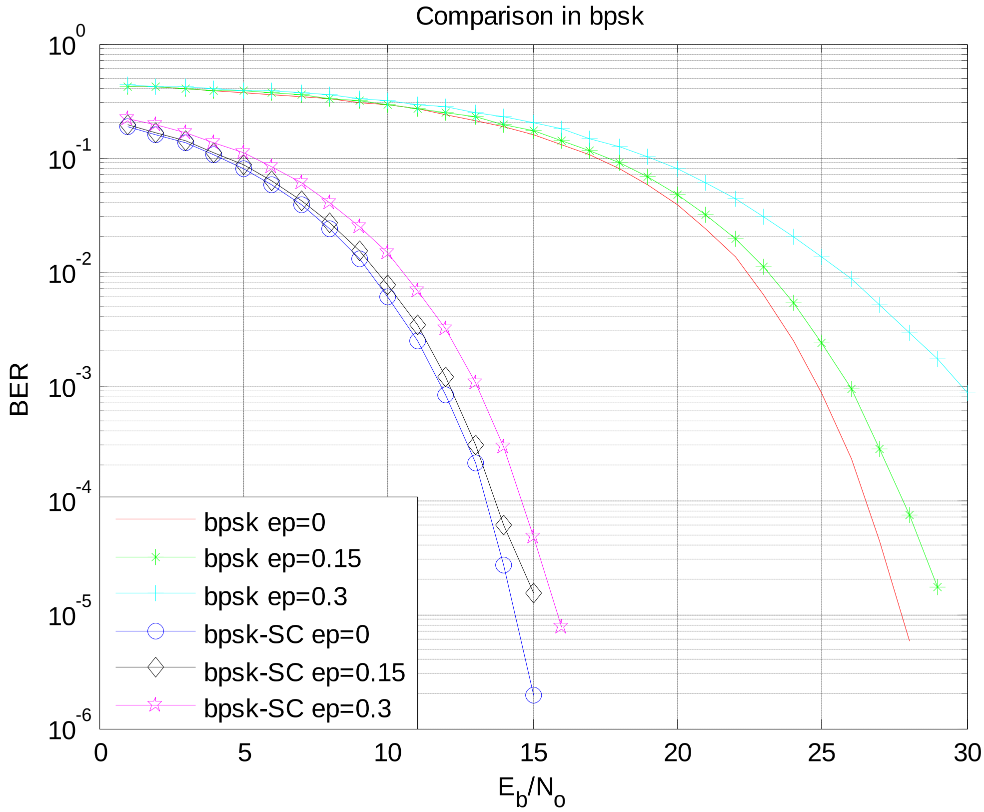


Fig. 6.4 BER performance of a BPSK OFDM system with & without Self Cancellation

This is the plot which shows the comparison between standard OFDM and OFDM with self cancellation technique for different values of frequency offset for the modulation BPSK. From the figure we observe that as the value of carrier frequency offset ε increases, the BER increases. We can infer that self cancellation technique in OFDM has less BER compared to without self cancellation.

6.3 BER performance of QPSK OFDM system

(a) BER performance of a standard QPSK OFDM system

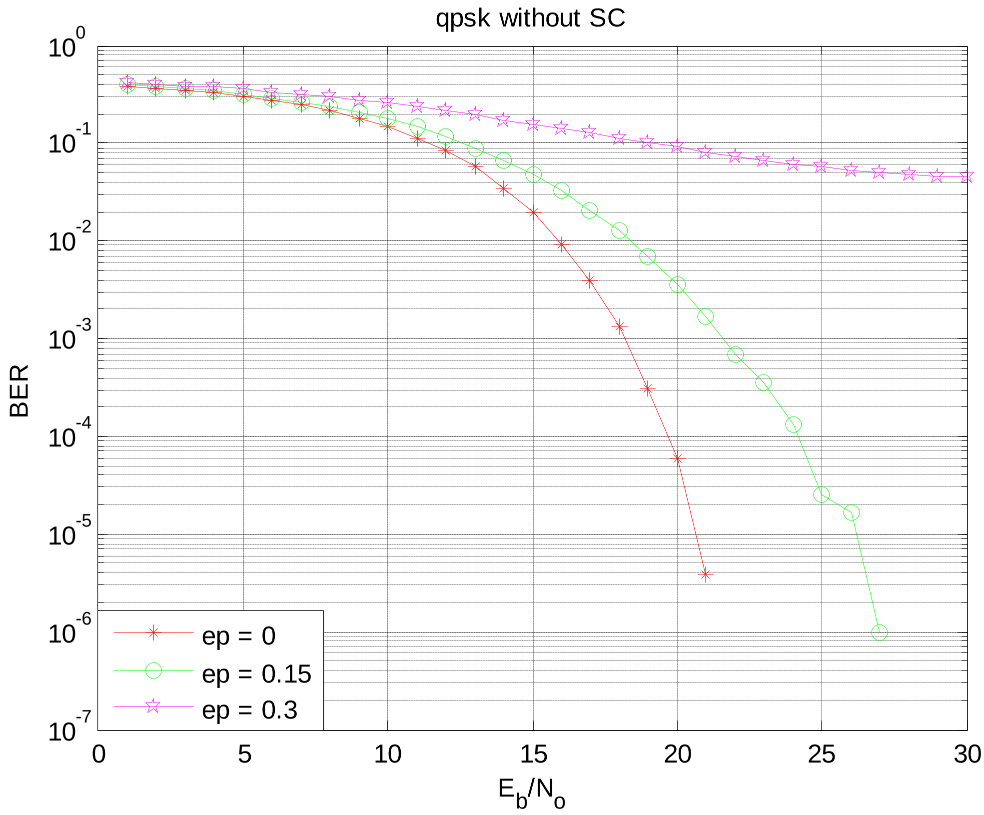


Fig. 6.5 BER performance of a QPSK OFDM system without Self Cancellation

This is the plot of BER vs SNR for QPSK without self cancellation for different values of carrier frequency offset. From the figure we observe that as the value of carrier frequency offset ε increases, the BER increases. As SNR increases QPSK BER curve leans downward which indicates reduction in bit error rate.

(b) BER performance of a QPSK OFDM system with Self Cancellation

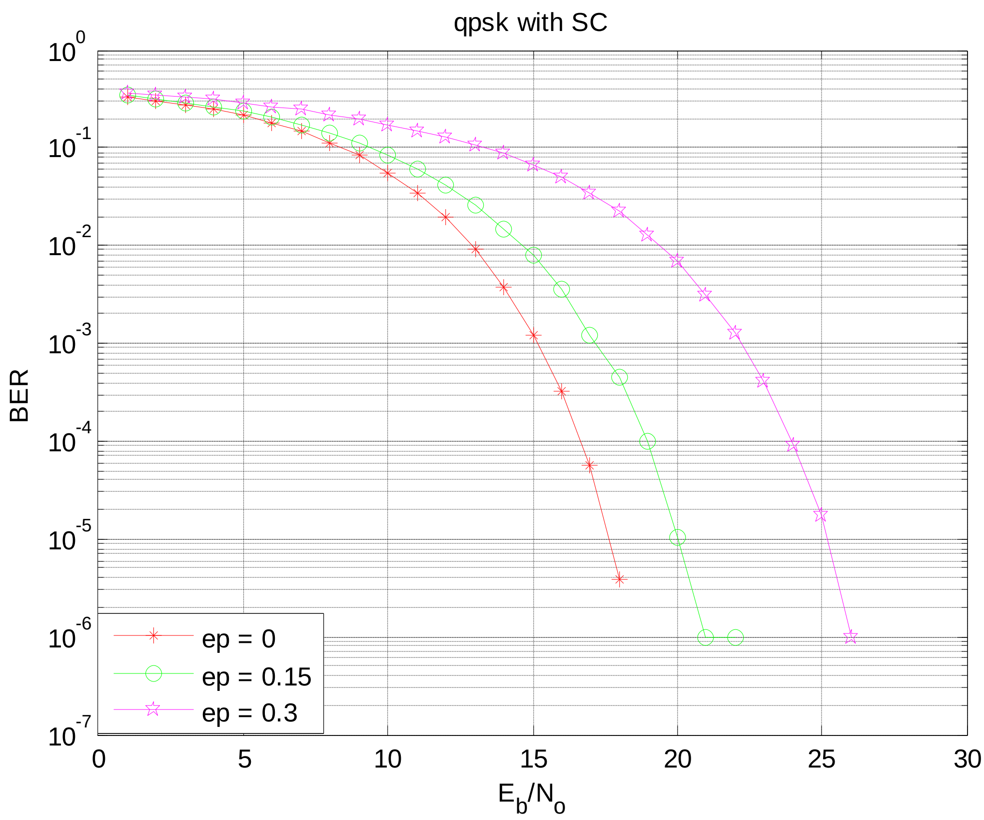


Fig. 6.6 BER performance of a QPSK OFDM system with Self Cancellation

From the figure we can conclude that as the value of carrier frequency offset ε increases, the BER increases. As SNR increases QPSK BER curve leans downward which indicates reduction in bit error rate.

(c) BER performance of a QPSK OFDM system with & without Self Cancellation

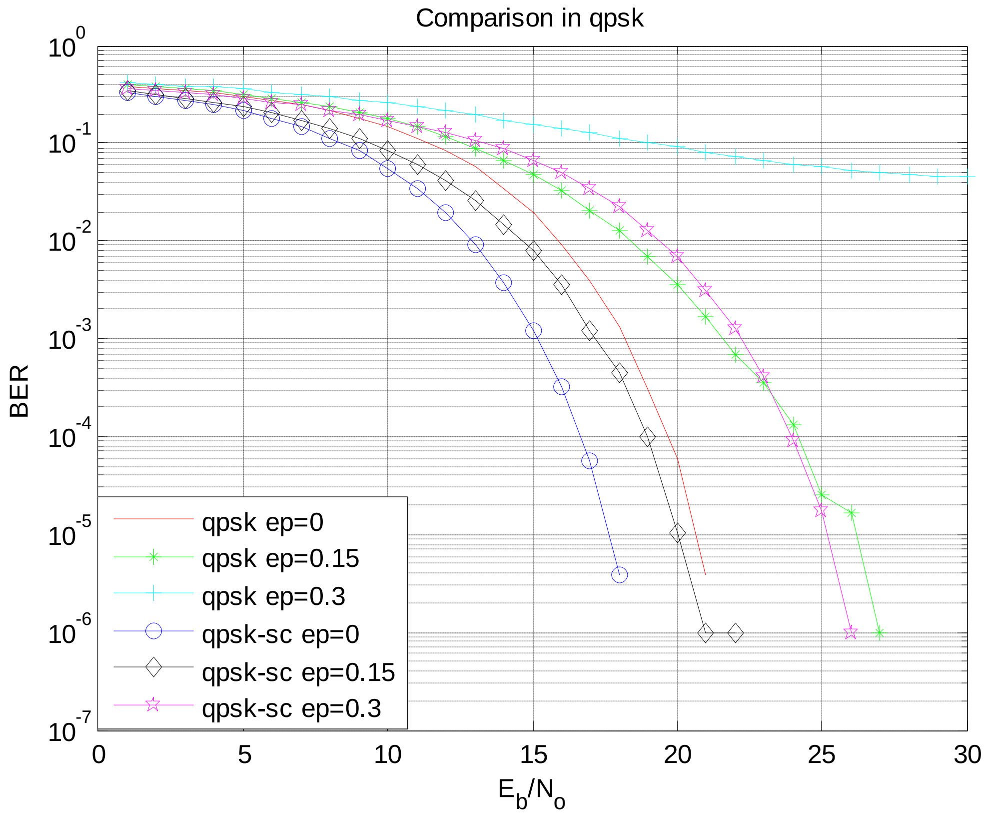


Fig.6.7 BER performance of a QPSK OFDM system with & without Self Cancellation

From the figure we observe that as the value of carrier frequency offset ε increases, the BER increases. As SNR increases QPSK BER curve leans downward which indicates reduction in bit error rate. This is the plot which shows the comparison between standard OFDM and OFDM with self cancellation technique for different values of frequency offset for the modulation QPSK. We can infer that self cancellation technique in OFDM has low BER compared to standard OFDM.

BER performances of QPSK, BPSK OFDM systems with constant frequency offsets.

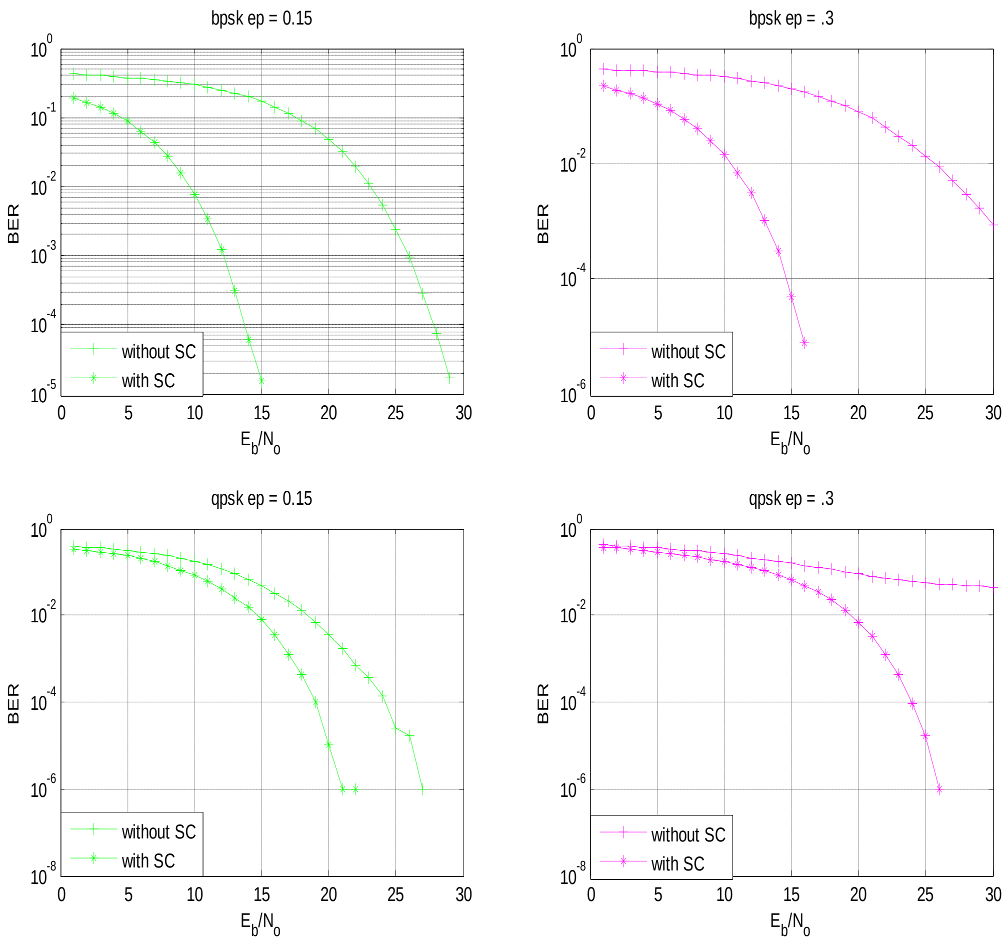


Fig.6.8 BER performances of QPSK, BPSK OFDM systems with constant frequency offsets

In these plots, the BER curve using self cancellation technique has low bit error rate. In BPSK as well as in QPSK, this technique is far better than standard OFDM system.

6.4 Comparison of BER performances of BPSK, QPSK OFDM systems

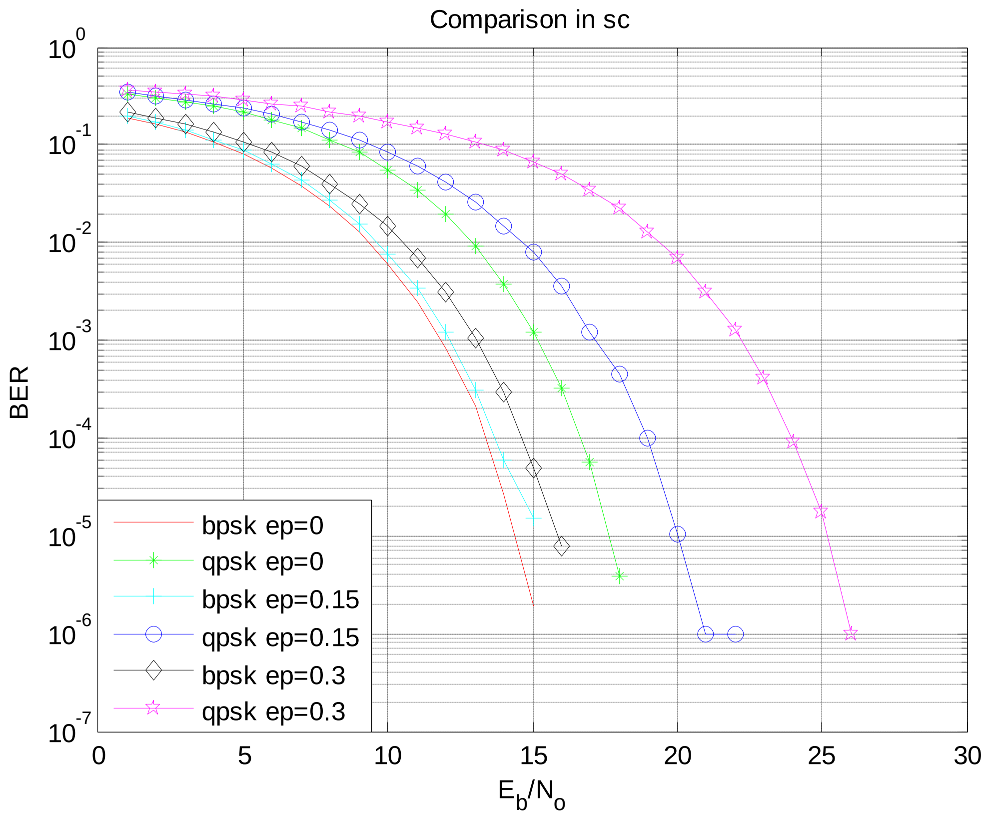


Fig.6.9 BER performance of a BPSK, QPSK OFDM systems with Self Cancellation.

This plot shows the comparison between two modulation techniques for different values of frequency offset. Here only self cancellation technique is considered. We notice that as the value of carrier frequency offset ε increases, the BER increases. For low frequency offset value BER is less. For constant ε value, BER of BPSK is less than BER of QPSK.

6.5 Simulated results based on Theoretical equations

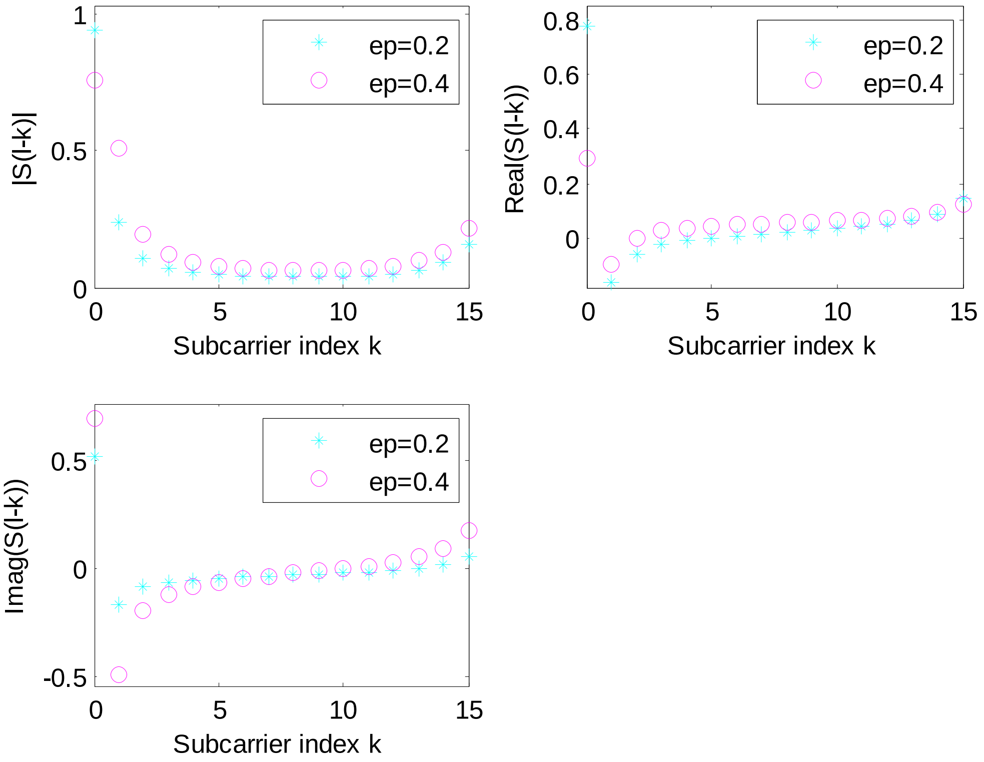


Figure 6.10

An example of $S(l - k)$ for $N = 16$; $l = 0$. (a) Amplitude of $S(l - k)$.

An example of $S(l - k)$ for $N = 16$; $l = 0$. (b) Real part of $S(l\text{-}k)$.

An example of $S(l - k)$ for $N = 16$; $l = 0$. (c) Imaginary part of $S(l\text{-}k)$.

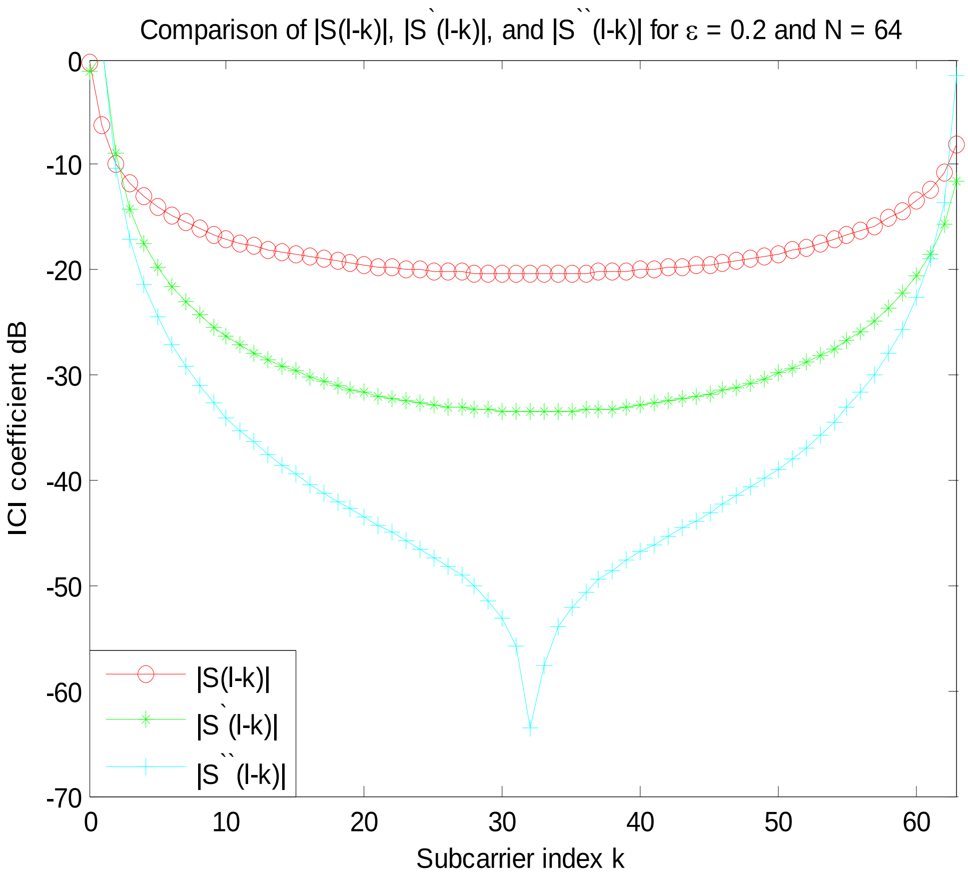


Fig. 6.11 comparison of |S(l-k)|, |S'(l-k)|, |S''(l-k)|

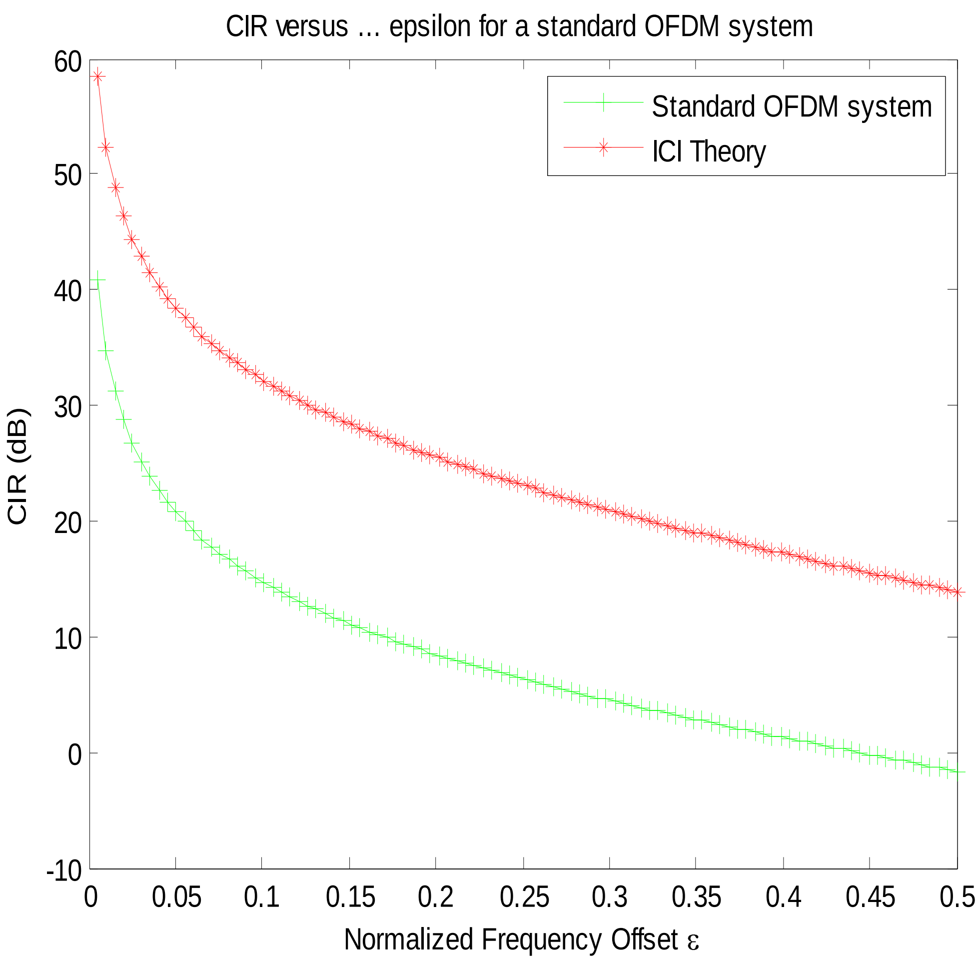


Fig. 6.12 CIR versus ε for a standard OFDM system and ICI theory

Chapter 7

conclusion

CONCLUSION

7.1 CONCLUSION

One of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes attenuation and rotation of subcarriers, and inter carrier interference (ICI).
Orthogonality of the sub-carriers in OFDM helps to extract the symbols at the receiver without interference with each other. Orthogonality is preserved as long as sub carriers are harmonics to each other. But if there frequency offset in the sub-carriers due to any reason then the orthogonality among them is lost & ICI occurs. The frequency offset is due to frequency mismatch between the transmitter and receiver local oscillators, and Doppler shift. The undesired ICI degrades the signal heavily and hence degrades the performance of the system.

So, ICI mitigation techniques are essential in improving the performance of an OFDM system in an environment which induces frequency offset error in the transmitted signal. This thesis work investigates an ICI self-cancellation scheme for combating the impact of ICI on OFDM systems for different frequency offset values. Different modulation techniques are considered for ICI reduction and compared with each other for their performances. It is also suitable for multipath fading channels. It is less complex and effective. The proposed scheme provides significant CIR improvement, which has been studied theoretically and by simulations. Under the condition of the same bandwidth efficiency and larger frequency offsets, the proposed OFDM system using the ICI self-cancellation scheme performs much better than standard OFDM systems. In addition, since no channel equalization is needed for reducing ICI, the proposed scheme is therefore easy to implement without increasing system complexity.

7.2 SCOPE OF FUTURE WORK

Following are the areas of future study which can be considered for further research work.

1. Coding associated with frequency (among carriers) and time interleaving make the system very robust in frequency selective fading. Hence Channel coding is very important in OFDM systems. COFDM (Coded OFDM) Systems can be used for ICI reduction using self cancellation technique.

2. This self cancellation technique can also be applied under different multipath propogation mobile conditions such as Rayleigh fading channel, urban, rural area channels etc.

3. This self cancellation scheme can be extended to Multiple input and Multiple output (MIMO) OFDM systems.

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